Isotopes & Radiation Technology

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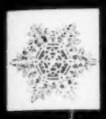

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by Isotopes
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TECHNICAL PROGRESS REVIEWS

The United States Atomic Energy Commission publishes the Technical Progress Reviews to meet the needs of industry and government for concise summaries of current nuclear developments. Each journal digests and evaluates the latest findings in a specific area of nuclear technology and science. *Nuclear Safety* is a bimonthly journal; the other two are quarterly journals.

Isotopes and Radiation Technology
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Reactor Technology
Prepared in cooperation with the American Nuclear Society

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Isotopes and Radiation Technology

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COVER: The E. F. lightning rod, used on many commercial buildings in Europe, has eight ^{241}Am sources promoting ionization of air. See page 179.

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Isotopes and Radiation Technology

is a Technical Progress Review prepared by the Isotopes Information Center, Oak Ridge National Laboratory, at the request of the Divisions of Technical Information and Isotopes Development, U. S. Atomic Energy Commission. This Review is intended to assist those interested in keeping abreast of significant developments in the fields of isotopes and radiation technology. It is not a comprehensive review of all literature published in this field during a given quarter; rather, it is a mechanism for presenting concise, selected reviews of information on subjects of prevailing Commission interest as it becomes available.

This Review attempts to relate the published results of research and development sponsored by the Division of Isotopes Development to significant developments in radioisotopes and radiation technology, as reported in the world literature. Coverage includes isotope production and development, isotope technology development, isotope applications technology, process radiation development, and radiation processing of food and medical supplies.

In addition to reviews of current literature and special review articles dealing with specific isotopes, facilities, and applications, this publication occasionally contains feature articles prepared by recognized experts on specific topics of current interest. Critical evaluations and interpretations presented are those of the editors and invited reviewers; therefore readers are encouraged to consult the original references in order to obtain all the background of the work reported and the interpretation of the results given by the original authors.

Insofar as feasible all references are checked by the editors, using the library facilities of Oak Ridge National Laboratory, Oak Ridge Associated Universities, and the University of Tennessee. Occasionally, however, the cited material is not available; such cases are identified by an asterisk (*).

The subject headings listed below have been adopted to help maintain continuity and order, from one issue to the next, in the material reviewed. All reviews, except Feature Articles, will be arranged under these headings; but any one issue will not necessarily contain all the headings.

Isotope Production and Development
Isotope Technology Development
Food Irradiation
Process Radiation Development
Source Development
Isotopic Heat and Power Development
Applications in Life Sciences
Safety
Isotopes Around the World
Miscellaneous

P. S. Baker, Robert H. Lafferty, Jr., Martha Gerrard, R. E. Greene, F. E. McKinney, and Helen P. Raaen, *Editors*
A. F. Rupp, *Adviser*

OAK RIDGE NATIONAL LABORATORY

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Section

I

Isotopes and Radiation Technology

Isotope Production and Development

The University of Missouri Research Reactor Facility

By A. H. Emmons,* E. L. Cox,† and D. M. Alger‡

Supplementary Keywords: *facility description; irradiator design; hot laboratory; ^{60}Co.*

Abstract: *The Research Reactor Facility at the University of Missouri in Columbia is described. This flux-trap reactor is designed to operate at 10 MW power but is currently operating at 5 MW. The reactor is cooled and moderated by light water and uses beryllium and graphite as reflectors. The laboratories and other facilities related to the reactor operation are also described.*

In the latter part of the 1950s, the University of Missouri recognized the potential of a nuclear reactor in university research activities. In the early stages of planning, the university decided it should provide a reactor of relatively high power and of unique design. This planning resulted in the University of Missouri Research Reactor Facility (RRF) located in the Research Park, south of the main campus of the University of Missouri in Columbia. The RRF was built to provide extensive nuclear science research facilities for education and for fundamental and applied research in the life, physical, and engineering sciences.

This nuclear research center is equipped to provide complete radiation science research service to the university. Included in the center are a 10-MW nuclear reactor, 17 scientific laboratories, a cobalt irradiation facility, a hot-cell facility, a neutron radiography facility, two counting rooms, two animal rooms, a photographic darkroom, a machine shop, an electronics shop, and an X-ray room.

Research in many diverse scientific disciplines is conducted by experimenters from the university's campuses at Columbia, Kansas City, Rolla, and St. Louis. The RRF is also available for use by researchers at other universities and from industry and government.

Construction of the center began in December 1963 and was completed in the spring of 1966. The reactor was designed for 10-MW operation; however, the cooling equipment initially installed limited operation to only 5 MW. The reactor first attained criticality in October 1966. A power level of 5 MW was reached in June 1967, and the reactor has been operating at this power since then. The current operating schedule is 24 hr/day, 5 days per week. Present plans call for additional cooling equipment to be installed, and reactor power to be increased to 10 MW in December 1970.

The RRF is administered as a part of the overall university system and is not associated with any single campus or department. The entire facility is under the direction of the Facility Director, who is responsible to the Vice-President for Academic Affairs. The director is aided in his duties by his senior staff consisting of the Associate Director, Assistant to the Director, Reactor Supervisor, and Manager of the Nuclear Science Group. The 36 staff members include professional chemists, nuclear engineers, reactor operators, and shop people, many of whom are also working on advanced degrees at the university. A number of the senior staff also hold academic positions in the university.

The director is also assisted by a Reactor Advisory Committee consisting of professors and officials of the university as appointed by the president of the

*Director of the Research Reactor Facility located in Columbia, Mo.

†Associate Director of the Research Reactor Facility.

‡Reactor Supervisor of the Research Reactor Facility.

university. The committee's responsibility is to provide periodic safety reviews of reactor and experimental operations. The committee membership represents expertise in many disciplines of science and engineering.

The primary purpose of the RRF is to provide outstanding, well-managed, safe radiation research services to faculty and students of the university. For further details on the facility and for information regarding a possible use, please contact the Director, Research Reactor Facility, Columbia, Mo. 65201.

RESEARCH REACTOR FACILITY

The RRF is 143 ft wide by 230 ft long (Fig. 1). The grade-level floor plan is shown in Fig. 2.

The reactor containment structure, located near the center of the facility, is four stories high and is surrounded at grade level by laboratories. This structure has five operating levels, one of which is belowground. The containment walls are poured concrete, and containment integrity is maintained at all times the reactor is operating. Entry and exit are permitted through an interlocked double-door passage at grade level. In addition to the reactor and associated shielding, the containment structure houses the reactor control room, offices, a laboratory, and equipment for experiments.

From the reactor control room, which is on the third level, the operator has a direct view of the reactor pool area (Fig. 3). He can observe experiments on the beam port floor directly (Fig. 4) or on the monitor of a remote TV camera system in the reactor control room. An observer on the beam port floor has the view of the reactor shown in Fig. 5.

Spent fuel is stored in the reactor pool. The fuel-storage racks are placed near a removable portion of the biological shield in such a manner that the spent fuel may be used as the source for a gamma irradiation facility. Recessed storage ports are built into the west concrete wall on the beam port floor for radioactive materials that have been removed from the reactor. These materials are stored until they have decayed to a level safe for disposal or reuse.

Fig. 1 The University of Missouri Research Reactor Facility.

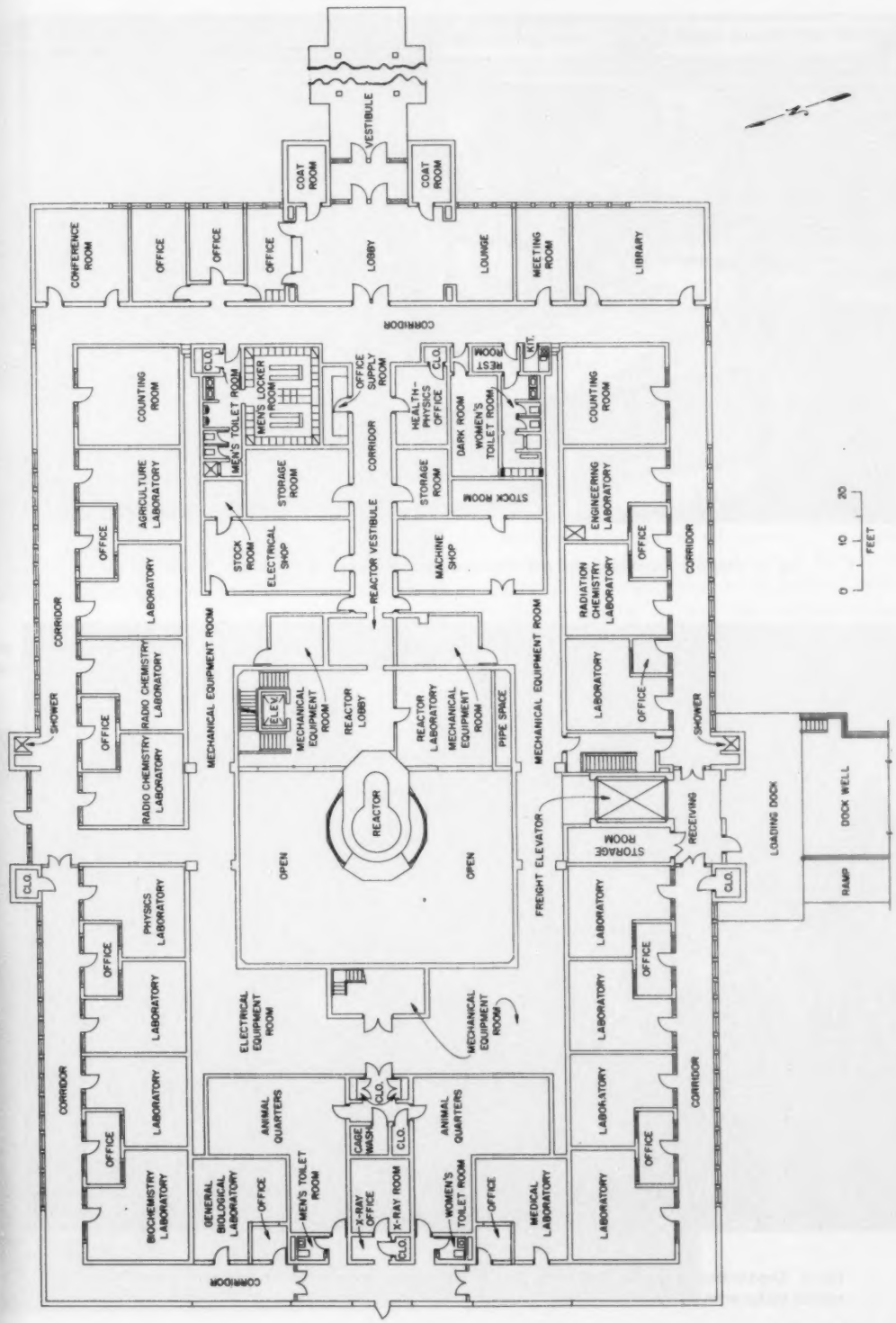

Fig. 2 Grade-level plan of the RRF.

Fig. 3 View of control room and top of reactor pool showing control-rod-drive mechanisms.

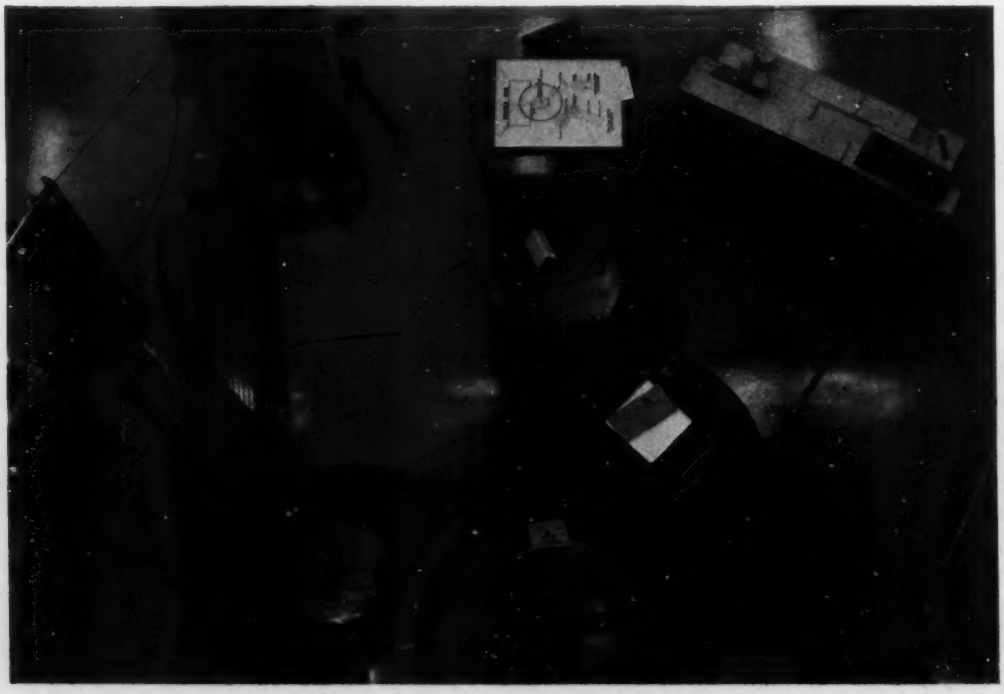

Fig. 4 Department of Physics dual-beam, double- and triple-axis neutron diffractometer as seen from reactor bridge level.

Fig. 5 Reactor biological shielding as viewed from beam port floor level.

LABORATORIES

The building that surrounds the reactor containment structure houses 17 research laboratories and adjacent offices. The laboratories are arranged on the periphery of the containment structure and enclose a central mechanical-equipment area. Each laboratory has a fume hood that discharges through particulate filters to a central exhaust system and then to the building exhaust stack.

A pneumatic-tube system rapidly transports samples into the reactor and returns them to certain laboratories. Four pneumatic-tube positions in the reactor service seven laboratories by means of switching stations. One laboratory send–receive station is shown in Fig. 6.

There are two radiation detection and measurement laboratories (counting rooms) in the laboratory building. In addition to other special counting equipment, such as a liquid scintillation counter and a low-background beta counter, these laboratories have a high-resolution gamma-ray spectrometer system consisting of a 45-cm^3 coaxial Ge(Li) detector coupled, through a preamplifier, to a Packard 4096 multichannel analyzer system. The readout equipment includes display oscilloscope, IBM 029 card punch, Franklin high-speed printer, tally punched paper tape,

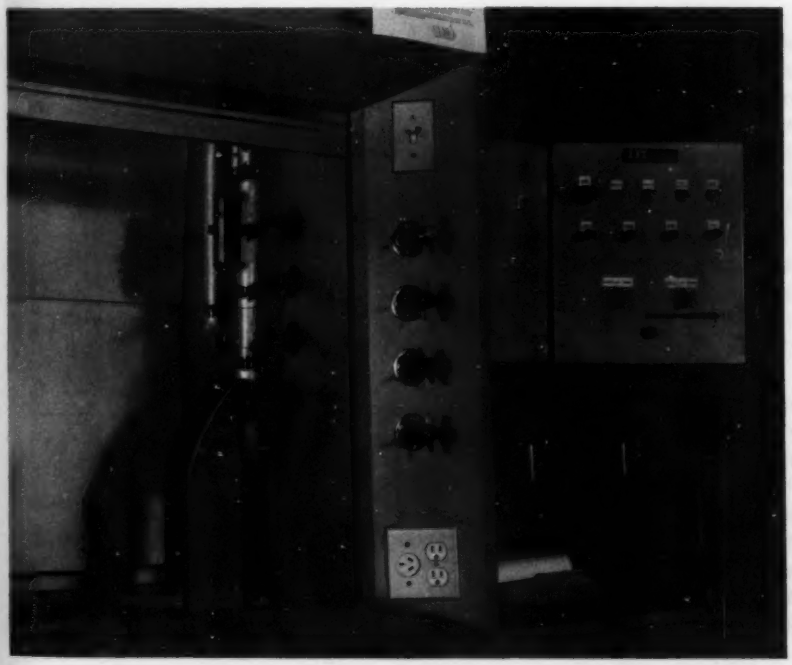

Fig. 6 View of laboratory fume hood showing pneumatic-tube terminal and transfer station.

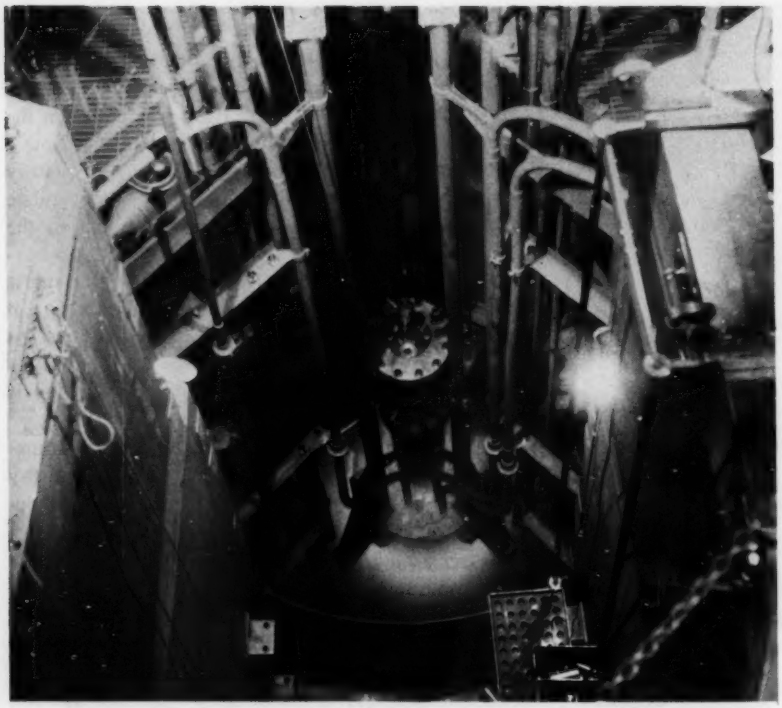

Fig. 7 Reactor operating at 5 MW located under 27 ft of demineralized light water.

magnetic tape with tag word identification, and omnigraphic analog plotter. Auxiliary electronic equipment includes two linear amplifiers and base-line restorers to provide separate front-end electronics for NaI(Tl) and Ge(Li) detectors, and a precision pulser and stabilizer to enhance the system stability. Also available is a high-resolution Si(Li) X-ray detector for use with the 4096 multichannel analyzer. The system can resolve 2.5 keV (FWHM for the 1.33-MeV ^{60}Co), with a peak-height-to-Compton ratio of approximately 26 : 1. Computerized, routine, multielement activation-analysis methods are being developed and evaluated.

RESEARCH REACTOR

The pressurized (60 psi) tank-type, flux-trap research reactor is fueled with uranium highly enriched in ^{235}U, is light-water moderated and cooled, has beryllium and graphite reflectors, is reflector controlled, and has forced-convection cooling systems.

The reactor is shown in operation in Fig. 7. The reactor core, an annular cylinder 12 in. in outside diameter and 24 in. high, consists of eight plate-type fuel elements (Fig. 8). The center of the core is unpressurized and contains the flux trap. Surrounding

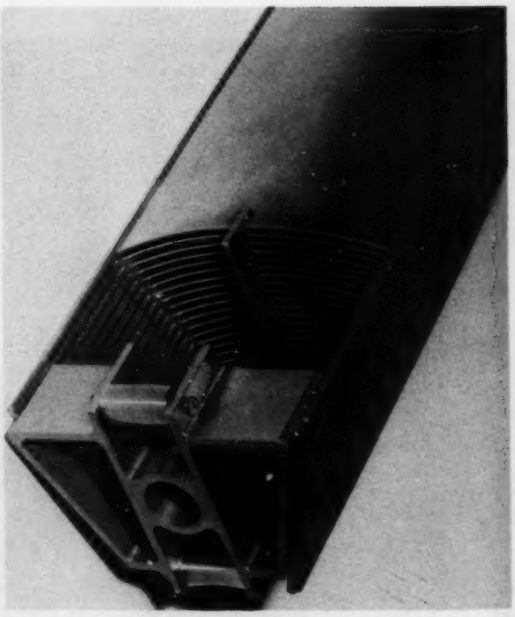

Fig. 8 An end view of one of eight fuel elements. Each element contains 650 g ^{235}U. The active core length is 24 in.

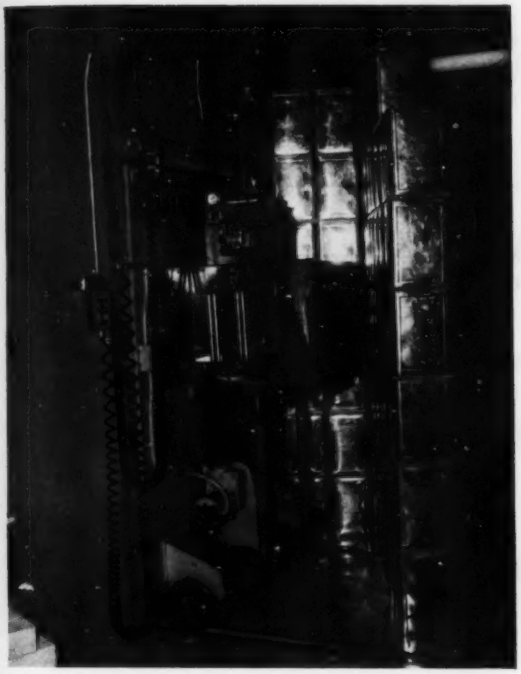

Fig. 9 The neutron radiography facility is installed in the reactor thermal column. Cans of borated water provide supplemental shielding to adjacent experiments.

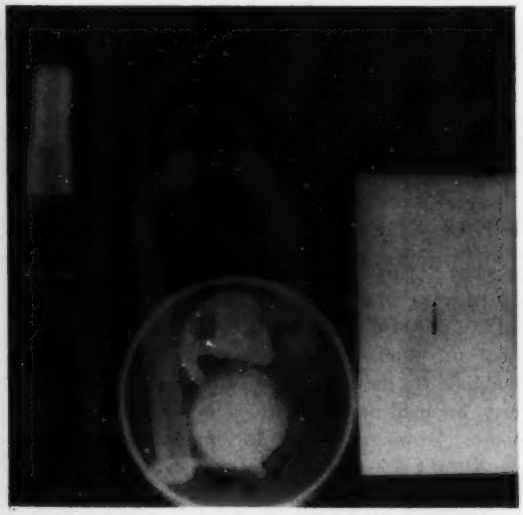

Fig. 10 Neutron radiograph of a padlock and a cadmium sheet obtained with the transfer technique using indium foil. The hole size in the cadmium sheet is 0.010 in. in diameter.

the core are, first, the beryllium reflector and, next, the graphite reflector. The control shroud consists of five independently movable blades in a water gap between the core and the beryllium reflector.

Since the prime purpose of the University of Missouri reactor is research, many different experiments are possible as a result of the design features:

- The flux trap provides the highest thermal flux and is accessible through a center hole which accommodates a hollow aluminum canister to hold the samples in the flux trap.
- A portion of the graphite reflector can also be used for irradiation experiments. Twelve sections of the reflector have holes for sample irradiation (see Fig. 11). Four are linked to the pneumatic-tube system. This system is a standard 1.5-in.-diameter vacuum-operated system, which can transport irradiation containers from the laboratories in the laboratory building into the reactor containment structure through the biological shield and to the reactor positions.
- The reactor has a thermal column for experiments with thermal neutrons. This thermal column is presently being used for neutron radiography (Fig. 9). Figure 10 shows a neutron radiograph taken without collimation. A collimator being constructed is expected to significantly enhance resolution. At present all radiographs are taken using a transfer technique with indium foil.
- The reactor has three 4-in.-diameter and three 6-in.-diameter beam tubes. These tubes provide collimated neutron beams from the reactor core to experiment positions located around the outside of the biological shield of the reactor. All six beam tubes penetrate the graphite reflector. Two of the 4-in. tubes also penetrate the beryllium reflector to provide a larger ratio of fast to thermal neutrons. To reduce the fast-neutron and gamma-ray background, one 4-in. and one 6-in. beam tube do not view the core directly, but terminate below the fuel level of the core. When a port is not being used for an experiment, a shield plug is installed and the port is flooded with water to complete the reactor shield.

Table 1 presents pertinent characteristics of the University of Missouri Research Reactor, and Table 2 provides neutron-flux data in the facility. The plan view of the reactor core region in Fig. 11 shows the experiment positions.

The data in Table 2 are for 5-MW power levels of operation. At 10 MW the flux in each position will approximately double.

Table 1 Summary of Pertinent Reactor Data

Power	
Initial power capability, MW	5
Eventual power with modification, MW	10
Average power density at 5 MW, kW/liter of core volume	151
Average power density at 10 MW, kW/liter of core volume	303
Reactor Core	
Geometry	Annular
Inner fuel radius, in.	2.66
Outer fuel radius, in.	5.90
Active fuel height, in.	24.0
Active volume of core, liters	33.0
Fuel loading for 5-MW operation, kg ^{235}U	5.2
Number of fuel elements	8
Fuel plates per element	24
Cladding of fuel plates	Aluminum
Coolant-gap thickness between plates, in.	0.080
Fuel-plate thickness, in.	0.050
Fuel thickness, in.	0.020
Cladding thickness, in.	0.015
Core Coolant	
Total flow rate at 5-MW operation, gal/min	1800
Coolant pressure, psia	65
Inlet temperature, °F	140
Outlet temperature, °F	157
Demineralizer flow, gal/min	50
Pool Coolant	
Flow rate at 5-MW operation, gal/min	400 to 600
Mixed pool temperature, °F	100
Pool inlet temperature, °F	99
Pool outlet temperature, °F	105
Demineralizer flow, gal/min	50
Assorted Characteristics	
Reactivity requirements ($\Delta k/k$) at 5 MW	0.0973
Rod worth (Δk)	0.259
Core lifetime, MWd	560
^{235}U consumed, kg/560 MWd	0.7
Reflectors	
Inner reflector	Beryllium
Inner reflector thickness, in.	2.71
Outer reflector	Graphite
Outer reflector thickness, in.	8.89
Height, in.	36
Coolant	Pool water
Control Rods	
Location	Outside vessel
Type	Curved plate
Material	Boral
Cladding	Aluminum
Overall thickness, in.	0.200

In addition to the positions shown in Table 2, a sector of the reactor pool is available for the irradiation of large items at flux levels up to 10^{12} n/(cm^2)(sec).

Table 2 Neutron Flux Available in the University of Missouri Research Reactor at 5 MW

Position	Thermal flux, n/(cm^2)(sec)	
Flux trap		
	3.7×10^{14} max.	
	2.3×10^{14} av.	
6-in. beam ports		
(1) Port B	5.3×10^{13}	
(2) Port D	3.0×10^{13}	
(3) Port E	5.0×10^{13}	
4-in. beam ports		
(1) Port A	7.5×10^{13}	
(2) Port C	3.0×10^{13}	
(3) Port F	7.5×10^{13}	
Pneumatic-tube system		
(1) Tube G-1	4.8×10^{13}	
(2) Tube G-2	3.9×10^{13}	
(3) Tube J-1	6.2×10^{13}	
(4) Tube J-2	4.3×10^{13}	
	Max.	**Av.**
Reflector positions		
(1) Position H-1	5.0×10^{13}	2.7×10^{13}
(2) Position I-1	5.0×10^{13}	2.7×10^{13}
(3) Position H-2	2.0×10^{13}	1.3×10^{13}
(4) Position I-2	2.0×10^{13}	1.3×10^{13}
(5) Position G-3	8.0×10^{12}	5.8×10^{12}
(6) Position H-3	8.0×10^{12}	5.8×10^{12}
(7) Position I-3	8.0×10^{12}	5.8×10^{12}
(8) Position J-3	8.0×10^{12}	5.8×10^{12}
Thermal column	Variable thermal flux from 10^{12} to 10^{8}	

IRRADIATION FACILITY

The ^{60}Co irradiation facility, which has an associated hot cell, is shown in Fig. 12. A source of up to 12 kCi of ^{60}Co can be safely contained in a 16-ft-deep pool of water in the basement of the laboratory building. By means of an elevator system, the source may be used for irradiations in air or water. The source, now amounting to approximately 4 kCi, consists of 10 stainless-steel-clad cylinders of ^{60}Co equally spaced on a circle that is 5.5 in. in diameter.

The associated hot cell is designed for multicurie levels of radioactive materials. The cell is equipped with leaded-glass shielding windows and two sets of master–slave manipulators. (RHL)

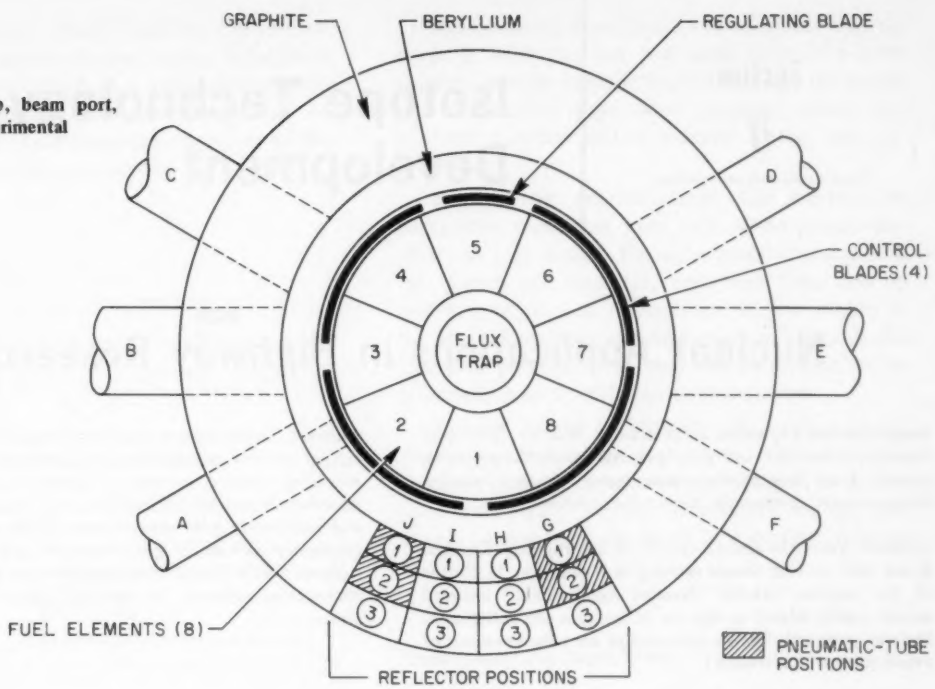

Fig. 11 Flux trap, beam port, and reflector experimental facilities.

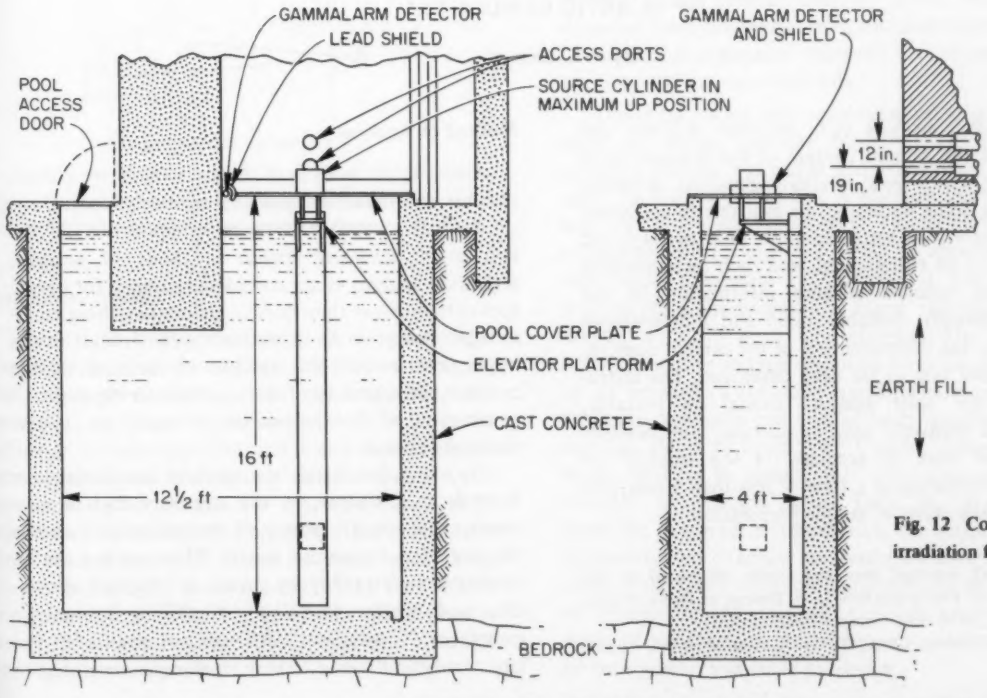

Fig. 12 Cobalt-60 in-air irradiation facility.

Section II

Isotopes and Radiation Technology

Isotope Technology Development

Nuclear Applications in Highway Research

Supplementary Keywords: *luminescence; industry; pollution; industry, stone, clay, and glass; polymerization; measurement, density; X-ray fluorescence; measurement, thickness; industry, transportation; comparison; backscatter; conference.*

[Editors' Note: On Jan. 12–16, 1970, the Highway Research Board held its 49th annual meeting in Washington, D. C. One of the sessions, entitled "Nuclear Applications," included several papers related to the use of isotopes and radiation in highway programs. The six items below are edited versions of papers given at that session.]

Abstract: *Several devices and/or techniques involving highway-related research are described: (1) a portable nuclear gage for measuring cement content of plastic concrete; (2) X-ray-fluorescence systems for analyzing lead in automobile exhaust and calcium in raw cement mix; (3) a dual-type gage for gamma-ray backscatter measurement of soil density; and (4) a self-luminous overhead traffic sign activated by ^{85}Kr. Polymer-impregnated concrete for highway applications is also discussed.*

PORTABLE NUCLEAR GAGE FOR MEASURING CEMENT CONTENT OF PLASTIC CONCRETE*

By P. F. Berry†

Rapid on-site analysis (i.e., between delivery and pouring) of the cement content of wet concrete is an outstanding requirement in civil engineering. A variety of methods, some nucleonic, are available to determine such parameters as water content, bulk density, and the degree of air entrainment, and such measurements can provide valuable advance information on the concrete strength. Suitably rapid and representative methods for the determination of the cement content, however, have not so far been developed. The instrumentation for such analyses should be portable, rugged, and relatively easy to operate. The measurement should have an accuracy of 0.3 sack/yd^3 or better, be completed in a time of less than 1 min, and require the minimum of sample preparation.

Method of Analysis

Quantitative analysis of cement in concrete is made possible by virtue of cement's relatively unique and substantially constant chemical composition. Of the two more common nuclear methods of analysis, activation analysis is not considered suitable for on-site application. X-ray-fluorescence techniques, using radioisotope sources of excitation, were found to be impractical in concrete analysis on account of the extreme heterogeneity of the samples over the depth of penetration of the fluorescence X rays—i.e., a few hundred microns.

On the other hand, the method considered here depends in principle on the relatively high atomic number and specific gravity of cement as compared to the rest of the concrete matrix. This contrast can be measured most readily by means of radiation absorption and scatter techniques employing low-energy gamma or X radiation. Although nonspecific, in the true analytical sense, these techniques are highly

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accurate for essentially binary mixtures and furthermore offer some latitude in the choice of radiation energy to reduce the effects of sample heterogeneity. The radiation emerging from the sample can be measured either in the transmission mode or in the backscatter mode, as illustrated in Fig. 1.

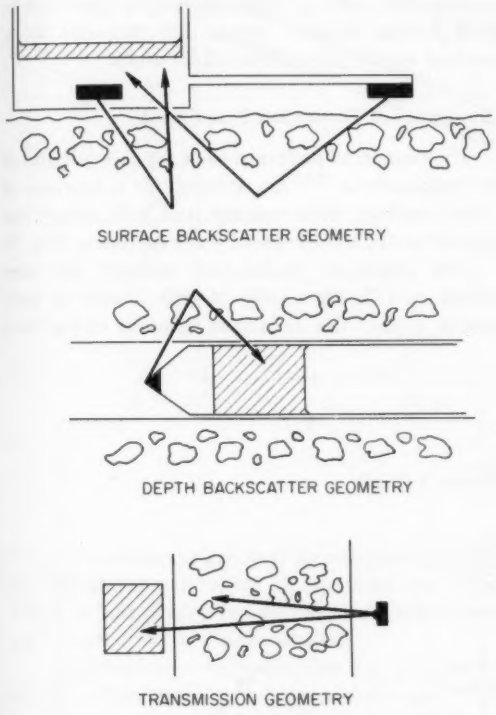

Fig. 1 Geometrical arrangements employing low-energy radiation scatter and transmission for cement analysis.

Preliminary Studies

During the investigation each of the geometrical arrangements of source and detector (shown in Fig. 1) was investigated with a view to establishing the sensitivity to changes in cement content and also the influence of aggregate size and composition, sample heterogeneity, and other sample variables such as water content and bulk density. The detectors were NaI(Tl) scintillation detectors with crystals of the appropriate dimensions; a variety of X- and low-energy gamma-ray sources including ^{241}Am (60 keV), ^{109}Cd (the 88-keV component), and ^{57}Co (122 keV) were used. A higher energy gamma-ray source, ^{137}Cs, was also used for bulk-density measurement.

Measurements were carried out on actual concrete mixes in both the wet and cured state. The latter samples, annular in shape to accommodate the depth-type backscatter gage, were prepared mainly for reference purposes and to evaluate further gage improvements.

Most of the experimentation has involved the backscatter techniques since they afford greater simplicity in gage design. The same probe contains both the source and detector, and thus there are no problems of physical displacement of one relative to the other. Variability of sample mass and shape is also less of a problem, since they can be arranged to be effectively infinite to the scattered radiation.

In view of the far superior performance of the depth-type backscatter probe over the surface-type geometry (which is sensitive to changes in surface conditions—e.g., surface free-water seepage and sample compaction), the depth-type configuration was adopted.

Studies with the Depth Probe

The depth probe consists of a 1-in.-diameter by 1-in.-thick NaI(Tl) crystal scintillation detector and a 2-mm-diameter spherical 14-mCi ^{241}Am source mounted on a conical radiation shield and axially separated from the crystal by a distance of about 2 in. The source-and-detector assembly is encased in a 0.020-in.-wall stainless-steel tube.

The initial backscatter measurements (Fig. 2) were made on simple concrete mixes to which no air-entrainment resin was added and which had a constant water content of about 7%. A siliceous aggregate was used in the usual proportion of 3 parts coarse (maximum size 1.5 in.) to 2 parts fine aggregate. Each data point represents the average of five discrete point-to-point measurements made throughout the sample, and the error bars represent the standard deviation in this average deduced from measurements on six remixes of the same sample. The error reflects the coarse aggregate and normal heterogeneity effects, and runs about ±0.1 sack/yd^3. Clearly, one would not be so naive as to assume that this is an achievable accuracy in practice. Apart from the problem of variations in aggregate composition, the major variables encountered in practice are water content and bulk density, the latter variation being induced deliberately by air-entrainment resin or occurring naturally as a result of variations in water content, cement content, air entrapment, and other properties.

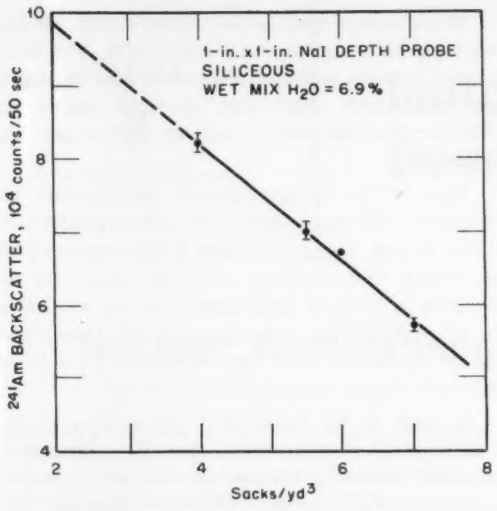

Fig. 2 ^{241}Am backscatter depth-probe response.

Effects of Variations in Water Content

The effects of variations in water content and bulk density were next investigated (Fig. 3). Although it may appear that variations in water content have a significant effect on the ^{241}Am backscatter intensity, the effect is only partially attributable to water content per se. Taking the results in Figs. 3*a* and *b* together, the principal effect appears to arise from an accompanying density change (as measured by a standard surface-type gamma scatter gage).

Comparison of Theory and Experiment[1]

The theoretical performance of the gage in terms of the backscattered ^{241}Am intensity as a function of cement content, water content, and bulk density has been calculated and compared with experiment (Fig. 4).

The americium backscatter intensity has been plotted as a function only of bulk density in each cement group. The calculated response curves have

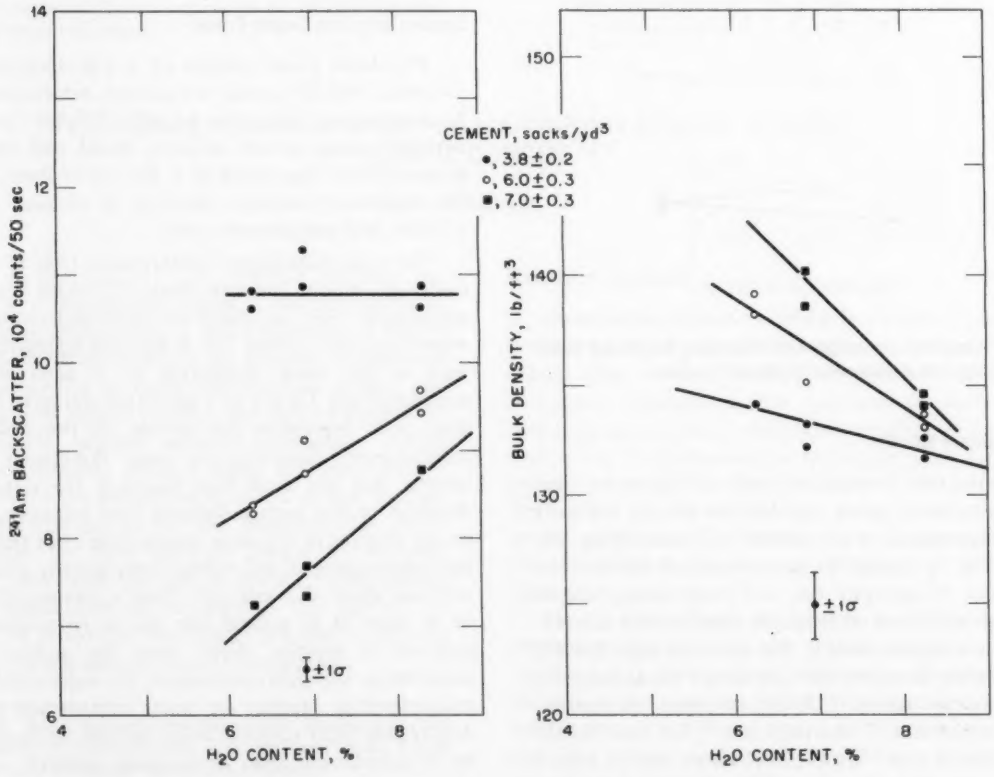

Fig. 3 Water-content effect on (*a*) backscatter intensity and (*b*) bulk density.

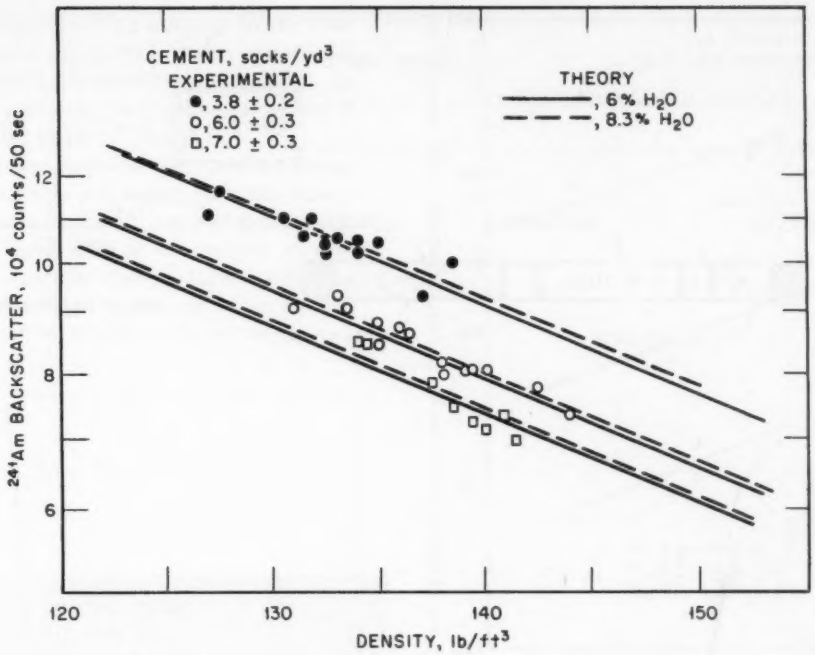

Fig. 4 Comparison of theory and experiment.

been normalized as a group to the experimental points, and agreement is excellent. In particular, the correlation with bulk density and the relative independence of water content per se should be noted.

The preliminary studies indicate that, for a particular type of aggregate, two measurements—an ^{241}Am backscatter measurement and a bulk-density measurement—will suffice to determine the cement content. Other sample variables, such as aggregate size, water content, and air entrainment, are automatically compensated for. Differences in type of aggregate (i.e., chemical composition) clearly dictate a separate calibration in each case. In this respect, our experience so far has been limited to only a few different types of aggregate, mainly of the siliceous type. For these aggregate mixes, a normalization procedure based on intensity measurements on a sample of the raw aggregate was sufficient. Since a sample of the aggregate is usually made available for other tests, calibration for each aggregate mix is a practical possibility.

Instrument Design and Performance

Design. The instrument comprises essentially two parts: the submersible probe unit, which contains the radiation detector and sources, and the electronic unit, which provides the detector high voltage, pulse amplification, and count-rate display. The main features of the probe layout are shown in Fig. 5. The density-measurement feature is provided within the probe and consists of a ^{137}Cs gamma-ray source located about 10 in. behind, and shielded from, the same detector that is used to detect the ^{241}Am scattered radiation. The assembly is hermetically encapsulated in an aluminum housing that can be mounted within the handheld accessory (Fig. 5) or within the sample-containing device (Fig. 6). The latter arrangement is recommended for the best accuracy for several reasons. In the first place, although the ^{241}Am intensity is not affected by the volume of sample presented to the gage (provided the radial dimension is more than 3 in. or so), the ^{137}Cs intensity is affected unless the volume is considerable (i.e., at least 6 in. around the probe). In the sample-containing device, the critical sample dimensions are held constant. A second feature of the containing device which promotes good accuracy is the built-in standardization block in which the probe is located before each measurement. (The lead shield that divides the measuring compartment from the standardizing compartment suppresses the nonrepresenta-

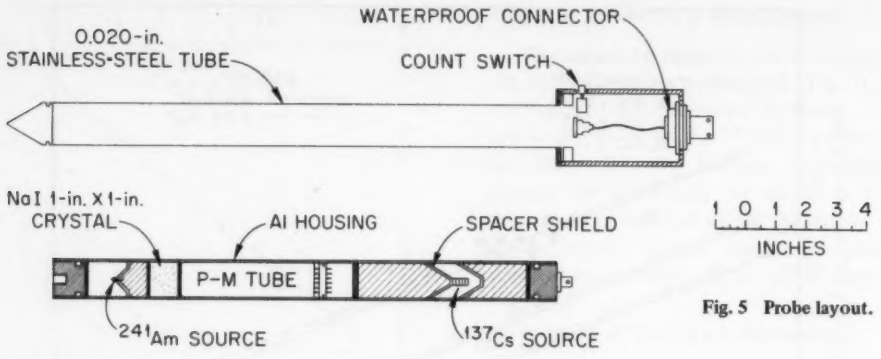

Fig. 5 Probe layout.

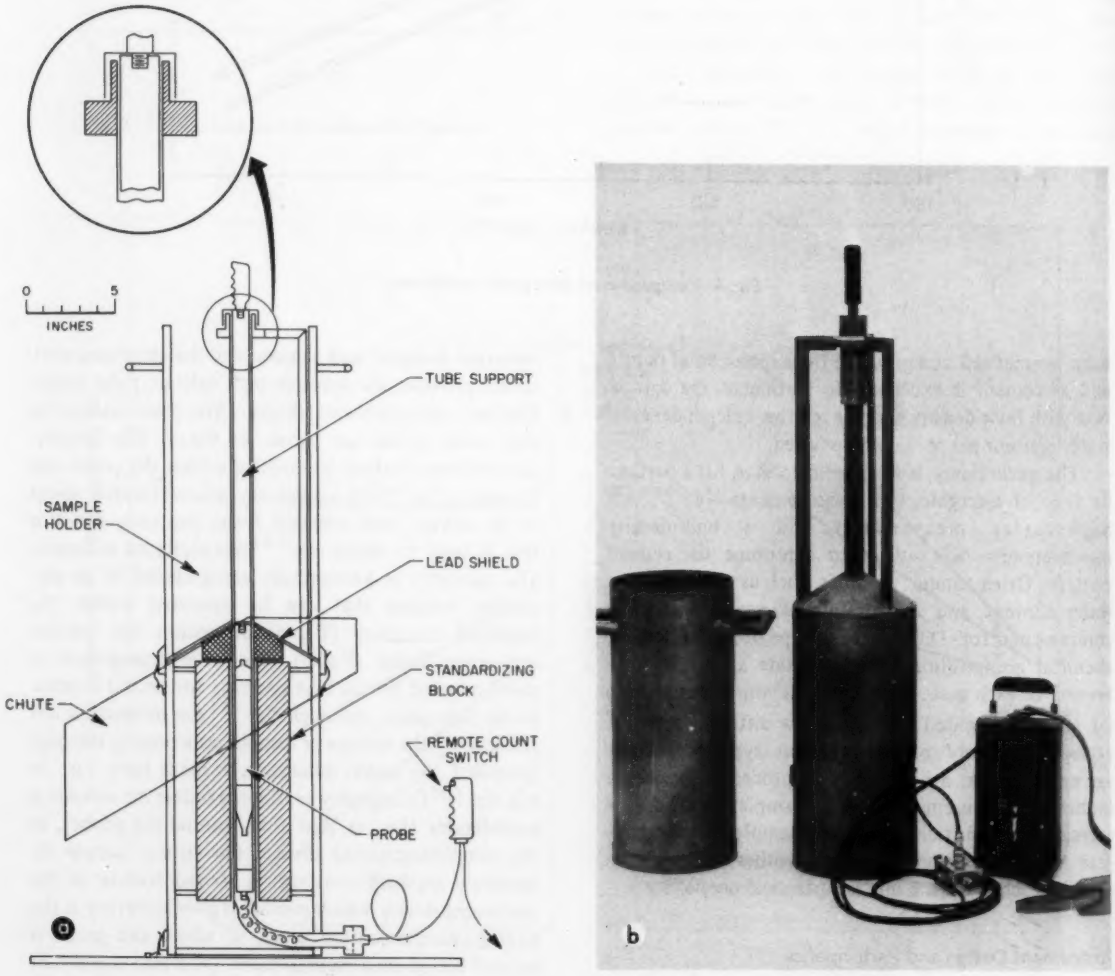

Fig. 6 (*a*) Wet-sample measuring device. (*b*) Actual photograph of device.

tive contribution of the ^{137}Cs intensity to the measured intensity until the probe is drawn up into the final position when both intensities are recorded. At the intermediate positions, the ^{241}Am measurement is relatively unaffected by the ^{137}Cs source.)

The backscattered radiation spectrums are shown in Fig. 7. The electronic unit employs a single-channel analyzer which is set on the ^{241}Am backscatter peak. Pulses above the upper level of the analyzer window are registered in a separate scaler contained within the unit. Either channel of information can be displayed at the end of the count by the throw of a switch.

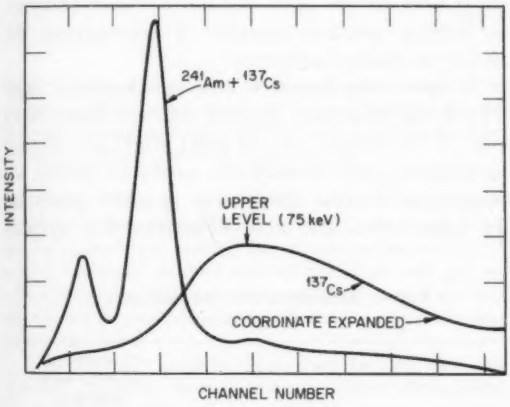

Fig. 7 Backscatter spectrums.

Preliminary Results. Some preliminary results with cured concrete annular blocks, using the dual-source probe, are shown in Fig. 8. These show the same pattern of behavior as those recorded earlier and establish the effectiveness of the density compensation. The estimated accuracy of these determinations is better than 0.3 sack/yd^3. The counting time in each measurement position was 20 sec, and the overall measurement time per sample was about 2 min.

Conclusion

The results obtained so far are certainly encouraging. Some improvements in the electronics are currently under way to provide better field operation—for example, to minimize the effects of electronic drift and gain variations. Further work on a wider variation of aggregate types has still to be carried out, and field tests have to be initiated. We expect the instrument to be available for these tests during early 1970.* (PSB)

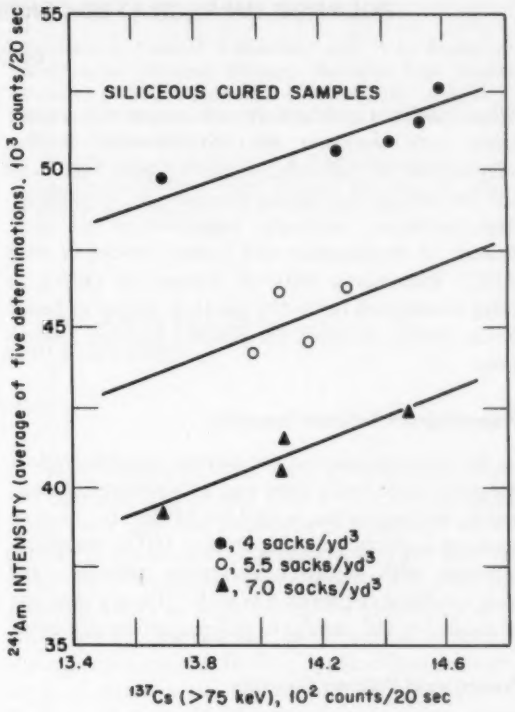

Fig. 8 Typical calibration nomograph.

*Editor's Note: The instrument was delivered to the U. S. Bureau of Public Roads in June 1970 for testing.

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POLYMER-IMPREGNATED CONCRETE FOR HIGHWAY APPLICATIONS

By R. G. Pike*

When hardened portland cement concrete is impregnated with monomer and the monomer is then polymerized by radiation, strengths almost four times the strength of the regular concrete can be obtained. This technique, originally suggested by the U. S. Bureau of Reclamation and jointly developed with AEC's Brookhaven National Laboratory (BNL), is being investigated further by the U. S. Bureau of Public Roads (BPR) and BNL for possible highway applications.

Preparation of Polymer Concrete

In the preparation of the polymer concrete, regular concrete, made in the usual way with portland cement, water, and aggregates, is aged for 28 days (or in some cases for a shorter period),, dried at 150°C, evacuated, saturated with methyl methacrylate monomer, and then irradiated for about 8 hr with ^{60}Co at a dose rate of about 5×10^5 rads/hr to polymerize the monomer.

Properties of Polymer Concrete

The engineering properties of the polymer concrete of major interest are listed[1] in Table 1, which compares the values obtained on regular (control) concrete and similar impregnated concrete. Preliminary estimates indicate that the cost per pound of a product (for example, concrete pipe) made with polymer concrete should be about double that of conventional concrete products; however, if full advantage can be taken of the increased strength of the polymer concrete by appropriate reduction in unit thickness, the cost of the finished product could be significantly less than that of the conventional product.

Applications of Polymer Concrete

One of the serious problems in the highway field is the deterioration of bridge decks and reinforcing steel, caused largely by the action of deicing salts under conditions of freezing and thawing. The polymer treatment greatly reduces the water permeability and water absorption of the concrete, which, in turn, is undoubtedly responsible for the greatly increased resistance to freezing and thawing (Table 1). Because of these greatly improved properties of the polymer concrete, BPR and BNL are investigating the feasibility of making precast polymer–concrete deck slabs and concrete pavements in place.

Preliminary tests have shown that the surface of concrete impregnated with polymer is much more resistant to abrasion than the surface of regular concrete. Such polymer concrete would help to preserve the nonskid properties of decks and pavement and should be of particular interest where studded tires are in common use. More research is needed, however, to develop practical methods of impregnating the surface of existing pavements.

A new safety feature recently developed for highways is the breakaway signpost and light post. However, if the weight of the poles could be reduced significantly, their breakability would be greatly increased, particularly when struck at lower speeds by the lighter cars. The BPR–BNL team has recently

Table 1 Summary of Properties of Concrete–Polymer Material

	Concrete control specimen (type II cement)	Concrete with up to 6.7 wt.% loading of polymethyl methacrylate, ^{60}Co gamma radiation polymerized
Compressive strength, psi	5,267	20,255
Tensile strength, psi	416	1,627
Modulus of elasticity, psi	3.5×10^6	6.3×10^6
Modulus of rupture, psi	739	2,637
Flexural modulus of elasticity, psi	4.3×10^6	6.2×10^6
Coefficient of expansion, in./(in.)(°F)	4.02×10^{-6}	5.36×10^{-6}
Thermal conductivity at 73°F (23°C), Btu/(ft)(hr)(°F)	1.332	1.306
Water permeability, ft/year	6.2×10^{-4}	0
Water absorption, %	5.3	0.29
Freeze–thaw durability		
Number of cycles	590	2,420
% wt. loss	26.5	0.5
Hardness-impact ("L" hammer)	32.0	55.3
Corrosion by 15% HCl (84-day exposure), % wt. loss	10.4	3.6
Corrosion by sulfates (300-day exposure), % expansion	0.144	0
Corrosion by distilled water	Severe attack	No attack

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developed a lightweight concrete (about 50 lb/ft^3) with a compressive strength greater than 2400 psi, and preliminary designs indicate that light poles made with this material may be feasible and better than those made with conventional materials.

For further details on the preparation technique and for results with other monomers, the reader should consult Refs. 1 and 2. (PSB)

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PORTABLE RADIOISOTOPE X-RAY ANALYZERS— TECHNIQUES AND APPLICATIONS

By J. R. Rhodes*

Supplementary Keywords: *X-ray fluorescence; coating; chemistry, analytical; measurement, thickness; industry, mining; industry; evaluation; source, gamma; instrument; measurement and control system; industry, primary metal.*

Abstract: *The recent development of sealed radioisotope sources that emit X rays and low-energy gamma rays and of simple methods for exciting and measuring characteristic X rays of elements, coupled with the use of portable battery-operated equipment, has made it possible to use the relatively sophisticated technique of X-ray-fluorescence analysis under field conditions.*

A number of "portable X-ray analyzers" are now commercially available. These instruments, whose characteristics are reviewed in this paper, weigh 12 lb and up, including batteries that have lives of 10 to 100 hr. They can perform quantitative analysis of any preselected element from calcium to uranium at concentration levels from 0.01 to 100%.

Many potential and actual applications for this type of instrument have been evaluated. These include measurement of the thickness of a wide variety of coatings and analysis of ores, pigments, powders, solutions, alloys, and slags. Some of these uses are summarized in this paper.

X-ray-fluorescence analysis is a sensitive and widely applied technique that until recently was thought of as purely a laboratory tool. However, in the last few years, small sealed radioisotope sources have been developed which can replace the X-ray tube and its high-voltage power supply. Also, greatly simplified methods of X-ray energy selection, based on X-ray filters, have been found adequate to isolate the characteristic X rays of the element to be determined. As a result, lightweight, portable, inexpensive X-ray-fluorescence analyzers have been developed for field and industrial use.

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Such instruments have been available since 1965 and manufactured in the United States since about 1968. Their main uses have been in rapid assay of ore samples in the field, in field laboratories, and even on ships. They have also found use in industry for analyzing alloys in scrap sorting, for identifying alloy types, and for checking the concentrations of electroplating bath solutions. In these applications the advantages of rapid in situ measurements are significant. Decisions that would otherwise have awaited a laboratory report can be made on the spot; the number of samples that have to be sent back to the laboratory can be reduced by an order of magnitude; and shipments of large quantities of the wrong alloy can be avoided.

The portable analyzers on the market at present are general-purpose instruments priced in the range $3000 to $5000. This is only a small fraction of the price of conventional laboratory equipment. X-ray analysis is thus available to people who have never before considered using it. As these people become more and more aware of the existence of such instruments, a wide range of new applications should be discovered. (Some of these ought to be large enough to justify development of special-purpose portable analyzers in an even lower price range.)

This paper points out the basic features common to these commercially available portable X-ray analyzers and summarizes some of their uses in elemental analysis.

Description of the Instrument

The first instrument[1-4] consisted of a 2-in.-diameter NaI(Tl) scintillation probe with balanced filters and an electronic unit that included an amplifier, single discriminator, and rate-meter readout. Most of

the instruments developed since then have used similar scintillation probes, but the sophistication and performance of the electronic units have been improved. The instruments now include a single-channel analyzer with variable window width and an up–down scaler for convenient display of the difference count from the balanced filters. A schematic of a typical instrument is shown in Fig. 1. Count times cover the range 10 to 100 sec, which is the usual range of convenience for the type of measurement undertaken. A great deal of

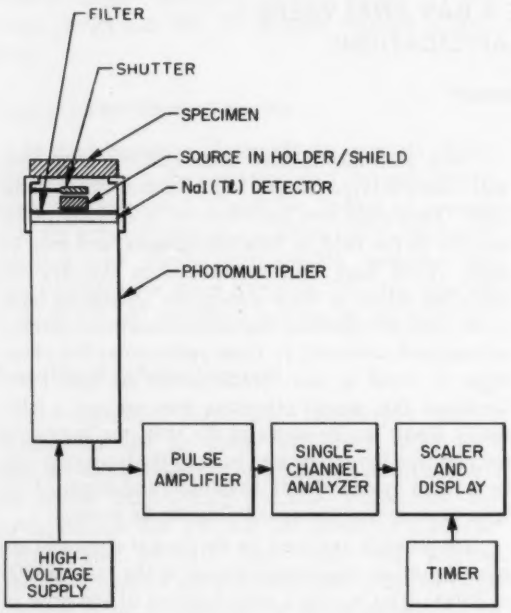

Fig. 1 Schematic of typical X-ray portable analyzer.

flexibility in power supplies is available, including line operation and operation from automobile batteries, rechargeable batteries, and dry cells. Battery life varies from 10 to 50 hr. Figure 2 is a photograph of one of the latest instruments. The instrument shown has a smaller scintillation probe than usual, 1.5 in. in diameter, and employs side-source geometry. The manufacturer* claims that improvements in geometrical design have significantly increased the sensitivity of the instrument in addition to permitting smaller specimens to be used than was hitherto possible.

*Columbia Scientific Industries, P. O. Box 6190, Austin, Tex. 78702.

Although proportional counters have better energy resolution than scintillation counters, their application to portable analyzers has been restricted to one or two instruments.[5-8] The probable reason for this is the high sensitivity of pulse height to count rate at the high count rates (10^3 to 10^5/sec) used in these instruments. Recently a reference source and gain stabilizer[5,7] have been used in an attempt to solve this problem. Furthermore, proportional counters are inefficient for detection of characteristic X rays with energies above about 15 keV.

Avalanche detectors[9] have also been developed to the point where they could be used in portable analyzers. They should find applications where their ultrasmall size outweighs their poor energy resolution.

Table 1 lists relevant properties of some of the instruments at present commercially available.

The principles of operation have been described in most of the references herein and, in particular, in an earlier article in this journal.[10] However, some important practical features are reviewed here.

Figure 3 shows four of the source–specimen–detector arrangements employed. The main objective is to attain highest geometrical efficiency concomitant with low background and relative insensitivity to specimen positioning. All the arrangements except collimated-beam geometry exhibit a so-called "count rate–distance plateau," and such a plateau is shown in Fig. 4. If the specimen is placed at the optimum distance, the maximum signal is obtained and there is good tolerance to changes in specimen distance. For measurement of rough material, however, it is sometimes preferable to position the measured surface farther away, on the linearly decreasing portion of the curve, so that the responses from peaks and valleys average out.

Figure 5 shows some typical response profiles across the specimen aperture of the probe. The central-source geometry shows the least uniform response.

Central-source geometry is the most widely used, while collimated-beam arrangements are hardly used at all, having little to recommend them. Annular-source arrangements have been used[2] to achieve a flat response profile. When optimized, the side-source arrangement combines maximum geometrical efficiency with minimum background, a good count rate–distance curve, and a practical response profile.

Applications

Portable analyzers are the first and only class of developed radioisotope X-ray-fluorescence instruments

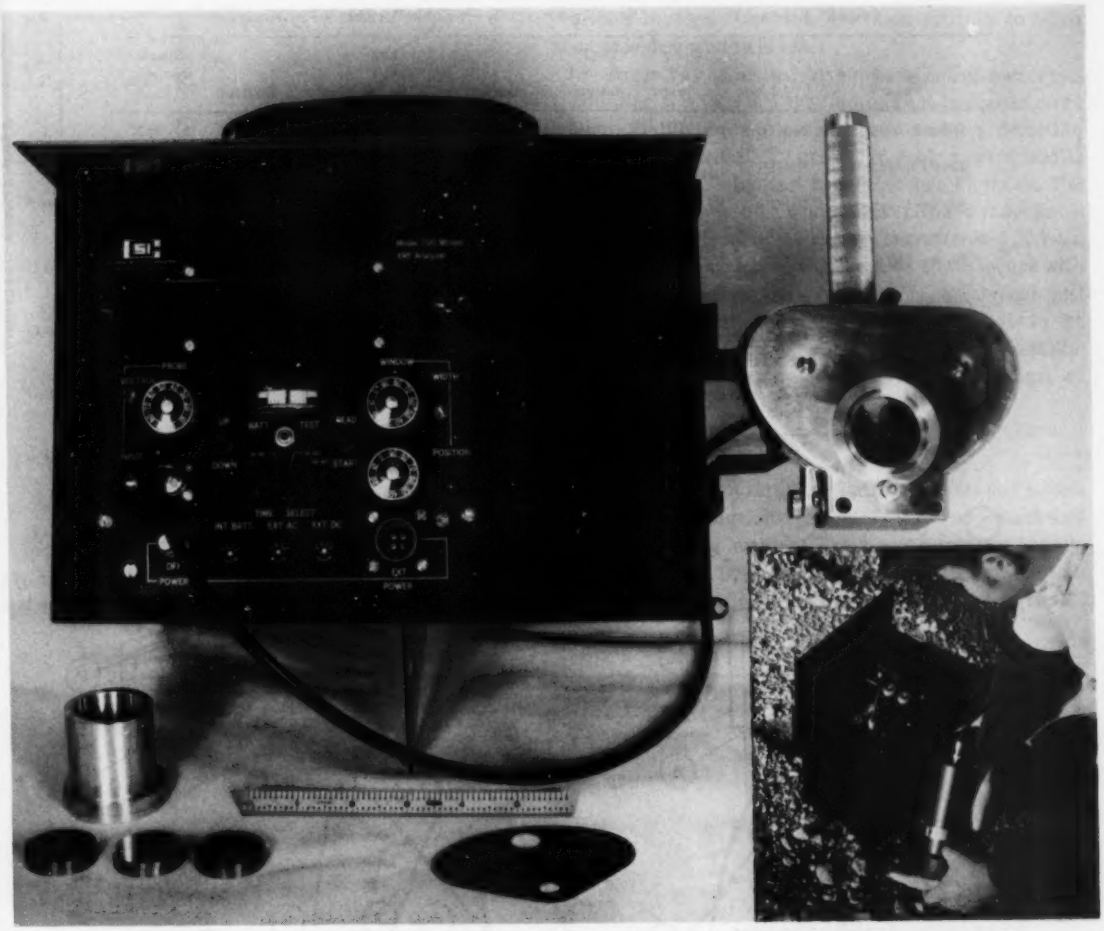

Fig. 2 Portable radioisotope X-ray-fluorescence analyzer. Inset shows use of instrument in field. (Courtesy of Columbia Scientific Industries Corporation.)

that have been in routine use long enough for systematic evaluations of a range of analyses to be available.[11-15]

Applications have been mainly to pulp, core, and rock-face analyses in mining, but other significant applications are to alloy and process-solution analyses. Elements from calcium to uranium can be determined with standard equipment using scintillation counters.

Nearly half of all the papers published in the last 3 years on radioisotope X-ray spectrometry describe portable analyzers and their applications in various industrial and field environments. It is probable that the number of portable analyzers in use is much greater than the number of papers written on their use, since the instruments have been commercially available for 5 years.

Table 2 classifies, alphabetically by element, the significant analyses reported in the past few years. A study of the published feasibility investigations reveals that in about 60% of them the objective was to optimize the accuracy of major component determinations, and in the rest it was to obtain the best possible sensitivity. In the former case the main sources of error are matrix effects. In field applications much ingenuity has gone into devising methods of minimizing these errors without compromising the essential simplicity of the equipment and measurement procedures. More development along these lines is expected, as matrix

Table 1 Relevant Properties of Some Commercially Available Portable X-Ray Analyzers

Maker	Probe	Filter pairs	Single-channel analyzer	Output	Battery life, hr	Probe	Readout	Sample diameter, in.
Hilger & Watts	NaI(Tl) 2 in.	1	No	Rate meter	100	3½	15	1½ to 2
Ekco Electronics	NaI(Tl) 2 in.	1	Yes	Scaler (10^6)	10	3½	14	1½ to 2
Nuclear Enterprises	NaI(Tl) 2 in.	1	Yes	Scaler or rate meter	10	3½	10	1½ to 2
Nuclear-Chicago	NaI(Tl) 2 in.	1	Yes	Scaler (6.4×10^5)	50	3	12	1½ to 2
Columbia Scientific Industries	NaI(Tl) 1½ in.	1	Yes	Scaler (10^6)	50	2	10	¾ to 1½
Panametrics	Proportional or scintillation	1	Yes	Scaler (6.4×10^5)	50	4	14	1½ to 2
Telsec	Twin proportional counter	6	Yes	Differential integrator	20–80	20	13	1½ to 2

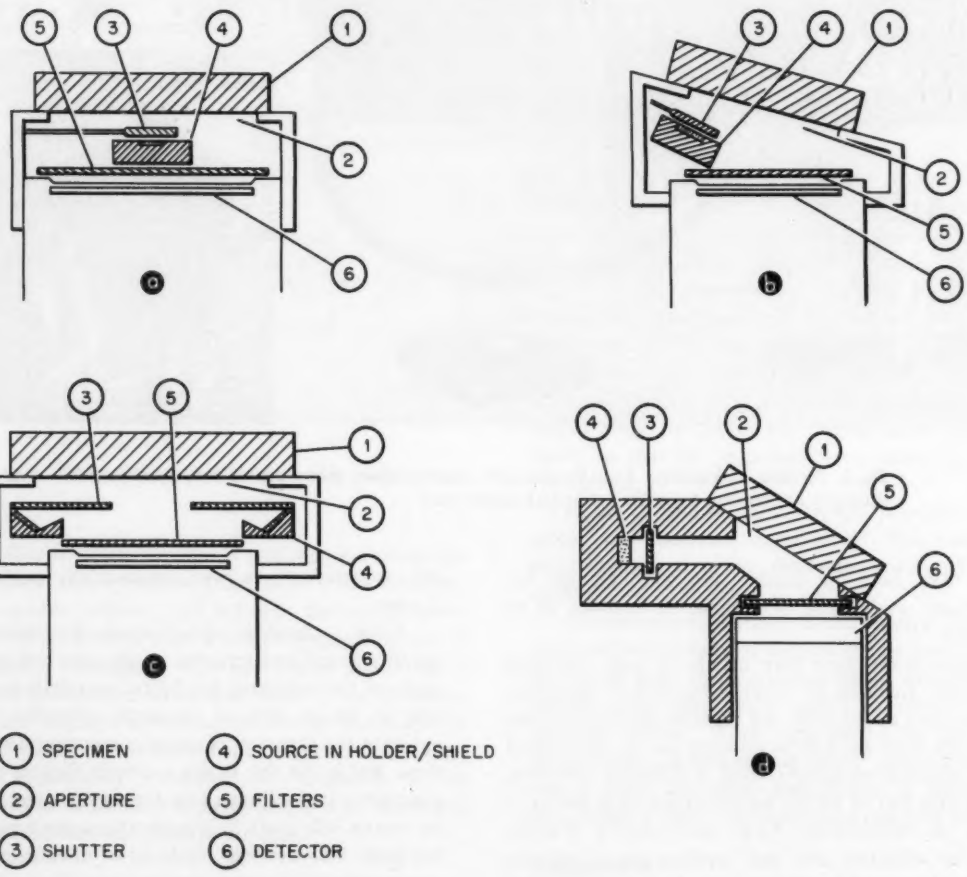

Fig. 3 Typical source–specimen–detector arrangements. (*a*) Central source. (*b*) Side source. (*c*) Annular source. (*d*) Collimated beam.

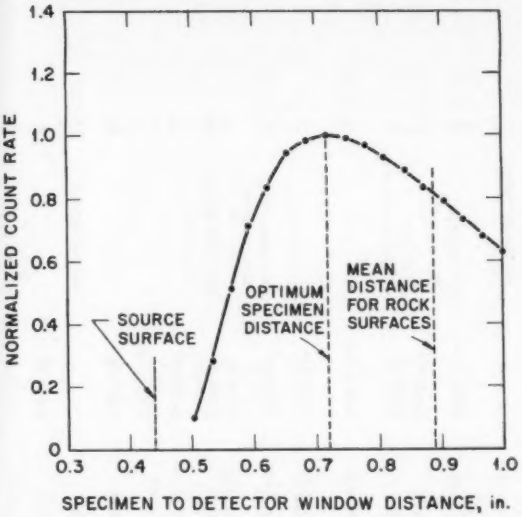

Fig. 4 Typical count rate–distance relationship for central- and side-source geometries.

effects appear to be one of the main obstacles to much more widespread field use.

Sensitivity is limited by the basic considerations of counting statistics and the fluorescence-to-scatter ratio. With scintillation and proportional counters, detection limits of about 0.03% (and in favorable cases, 0.005%) can usually be obtained by one of two methods. The first is to use a source whose backscattered radiation is just resolved from the required characteristic X rays. The second is to excite the required fluorescence with maximum possible efficiency using an energy just above the absorption edge of the element to be determined. Resolution limitations prevent the simultaneous use of these methods with proportional or scintillation counters.

Conclusions

Portable analyzers using balanced filters and scintillation or proportional detectors have an established and developing market. The basic technique is fully developed, but the range of applications is by no means fully explored or exploited. (RHL)

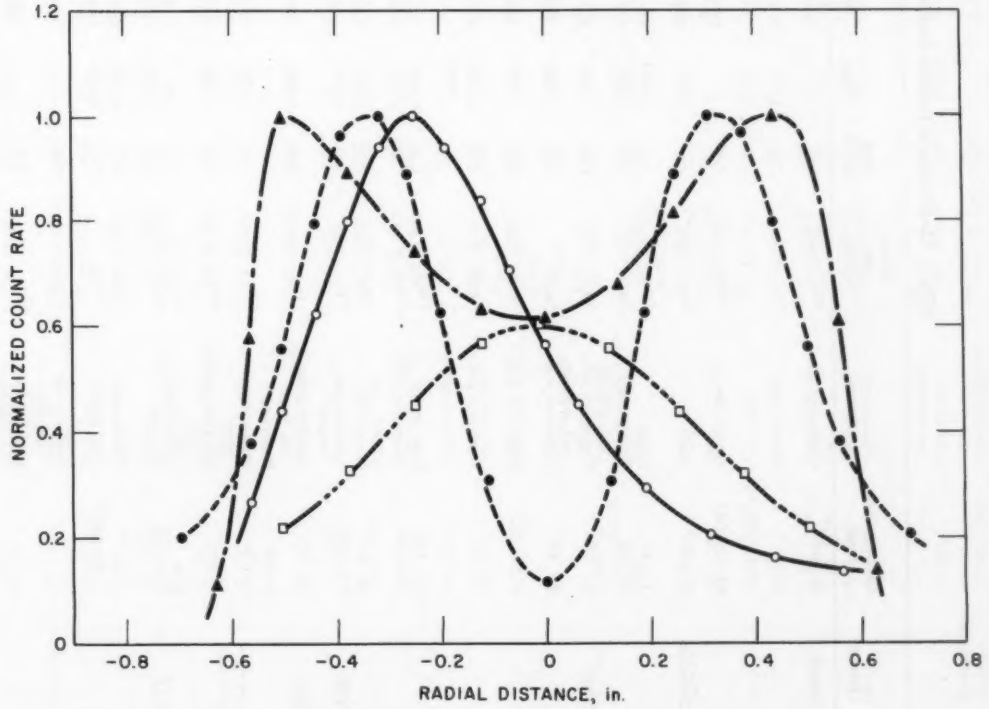

Fig. 5 Detector-response profiles across specimen apertures. •, central source; ▲, annular source; ○, side source (axis through source); □, side source (perpendicular axis).

Table 2 Classification of Portable-Analyzer Analysis Applications

Element	Concentration range	Material	Source and activity	X-ray excited	Filters	Detector	Application	Detection limit*	Remarks	Refs.
Calcium	40–50%	Cement raw mix	^{55}Fe, 2 mCi	CaK	–	Scintillation	Feasibility study	0.2% CaO*		16
	1–5%	Silicate rocks	^{55}Fe, 10 mCi	CaK	K/Ca	Si avalanche diode	Soil- and rock-type identification	0.5% CaO*	Also see under K	9, 17
	42–52% CaO	Cement raw mix	^{109}Cd, 1 mCi	CaK	–	Proportional	Feasibility study	0.17% CaO*	Reduced particle-size effects	18, 19
Chromium	1–20%	Steels	^{55}Fe, 7 mCi; ^{3}H/Zr, 2.5 Ci	CrK	Ti/V	Scintillation	Alloy analysis	0.1% Cr*		4
	0.5–8%	Steels	^{238}Pu, 20 mCi	CrK	Ti/V	Scintillation	Alloy analysis	0.15% Cr*		16
	0.5–5%	Electroplating bath solutions	^{3}H/Zr, 4 Ci	CrK	Ti/V	Scintillation	Feasibility study	0.15% Cr		20
Copper	0.1–15%	Copper-ore pulps and rock faces	^{3}H/Zr, 12 Ci	CuK	Co/Ni	Scintillation	Field assay	0.2% Cu*		2, 11, 13
	0.4–4%	Copper-ore pulps	^{3}H/Zr	CuK	Co/Ni	Scintillation	Draw control and sublevel caving	0.1% Cu*		21
	0.03–2.5%	Copper-ore pulps	^{109}Cd, 1 mCi	CuK	Co/Ni	Scintillation	Feasibility study	0.03% Cu		16
	0.1–5%	Copper-ore pulps	^{3}H/Zr, 2.5 Ci	CuK	Cr/Mn, Ni/Co	Scintillation	Feasibility study	0.2% Cu*	Special method for eliminating matrix effects	22, 23
	0.1–10%	Core samples	^{238}Pu, 30 mCi	CuK	Co/Ni	Scintillation	Core analysis			24
	0.4–1.6%	Manganese nodule pulps	^{238}Pu, 20 mCi	CuK	Co/Ni	Scintillation	Shipboard assay	0.05% Cu*	Also see under Ni, Fe and Mn	25
	60–95%	Copper alloys	^{109}Cd, 2 mCi	CuK	Co/Ni	Scintillation	Alloy sorting	0.45% Cu*		4
Gold	0.01–1%	Simulated ore samples	^{57}Co, 1 mCi	AuK	Hf/W	Scintillation	Feasibility study	0.03% Au		20
Iron	20–70%	Iron ores (pulps and cores)	^{238}Pu, 30 mCi	FeK	Cr/Mn	Scintillation	Field assay, mine control	0.5% Fe*		14, 19, 26
	1–10%	Pb/Zn ores								
	2–12%	Manganese nodule pulps	^{238}Pu, 20 mCi	FeK	Cr/Mn	Scintillation	Shipboard assay	0.24% Fe*		25
	5–50%	Iron ores (crushed rock)	^{238}Pu, 10 mCi	FeK	Cr/Mn	Scintillation	Strip-mine control	~1% Fe*	X-ray backscatter also considered	19, 27–29
	0.1%	Lubricating oil	^{3}H/Zr, 2 Ci	FeK	Fe	G–M tube	Wear monitoring	0.01% Fe		19
Lead	0.05–30%	Ore pulps	^{238}Pu, 30 mCi	PbL	Ga/Ge	Scintillation	Field analysis	0.08% Pb	Matrix and particle size studied	30
	1–8%	Core samples	^{238}Pu, 30 mCi	PbL	Ga/Ge	Scintillation	Core analysis	2% Pb*		24
	5–50 μg/cm^2	Filter paper	^{109}Cd	PbL	Ga/Ge	Proportional	Pollution monitoring	5 μg Pb		31
		Lead ores and mine walls	^{57}Co	PbK	–	Scintillation	Mine control	0.25% Pb		32
		Lead ores and core samples	^{75}Se	PbK	–	Scintillation	Field assay	–	Used nomograms	33–35
	0.05–3%	Leaded brass and steels	^{153}Gd, 0.6 mCi	PbK	W/Ir	Scintillation	Alloy sorting	0.05% Pb		4
		Manganese nodule	^{238}Pu, 20 mCi	MnK	V/Cr	Scintillation	Shipboard assay	0.75% Mn*	Also see under	25

		steels								4
Manganese	20–40%	Manganese nodule pulps	^{238}Pu, 20 mCi	MnK	V/Cr	Scintillation	Shipboard assay	0.75% Mn*	Also see under Fe, Cu, Ni	25
	0.2–1.5%	Steels	^{3}H/Zr, 214 Ci	MnK	V/Cr	Scintillation	Alloy sorting	0.14% Mn*		4
	0.5–5%	Plating bath solutions	^{238}Pu, 20 mCi	MnK	V/Cr	Scintillation	Feasibility study	0.04% Mn		20
Molybdenum	0.01–1%	Ore pulps	^{109}Cd, 2 mCi	MoK	Y/Zr	Scintillation	Mine control	0.01% Mo		14, 26
	1–20%	Copper concentrates								
	0.001–0.3%	Ore pulps	^{109}Cd, 1 mCi	MoK	Y/Zr	Scintillation	Feasibility study	0.003% Mo		20
	0.01–5%	Steels	^{109}Cd, 2 mCi	MoK	Y/Zr	Scintillation	Alloy sorting	0.04% Mo		4
	0.1–10%	Steels	^{109}Cd, 1 mCi	MoK	Y/Zr	Scintillation	Alloy analysis	0.1% Mo*		16
Nickel	0.8–1.6%	Manganese nodule pulps	^{238}Pu, 20 mCi	NiK	Fe/Co	Scintillation	Shipboard assay	0.05% Ni*	Also see under Fe, Cu, and Mn	25
	3–30%	Copper alloys	^{3}H/Zr, 2.5 Ci	NiK	Fe/Co	Scintillation	Alloy sorting	0.3% Ni		4
Niobium	0.06–2%	Steels	^{109}Cd, 2 mCi	NbK	Sr/Y	Scintillation	Alloy analysis	0.06% Nb		4
Potassium	1–5%	Silicate rocks	^{55}Fe, 10 mCi	KK	Cl/K	Si avalanche diode	Soil- and rock-type identification	~0.5%*	Also see under Ca	9, 17
Silver	0.01–0.1%	Silver-bearing ores	^{147}Pm/Al, 0.5 Ci	AgK	Mo/Rh	Scintillation	Field assay	0.003% Ag		38
Sulfur	0.1–5%	Pulverized coal	^{3}H/Ti, 5 Ci	SK	P/S	Scintillation	Feasibility study	0.17% S	Low-noise photomultiplier used	16
Tin	0.05–25%	Tin-ore pulps	^{147}Pm/Al, 0.5 Ci	SnK	Ag/Pd	Scintillation	Mine control	0.03% Sn		1, 2, 11
	0.5–5%	Tin mineralization	^{147}Pm/Al, 0.5 Ci	SnK	Ag/Pd	Scintillation	In situ assay of rock faces	0.1% Sn		2, 13, 36
	0.5–5%	Tin mineralization	^{35}S/Ba	SnK	–	Scintillation	In situ assay of rock faces	0.1% Sn		32
	0.5–5%	Tin ores, cores	^{147}Pm/Al, 0.5 Ci	SnK	Ag/Pd	Scintillation	Core analysis	0.1% Sn		2, 24
	0.002–0.1%	Tin mineralization	^{147}Pm/Al, 0.5 Ci	SnK	Ag/Pd	Scintillation	Geochemical prospecting	0.005% Sn	Feasibility study	37
	0.1–11%	Bronzes and gun metals	^{147}Pm/Al, 0.5 Ci	SnK	Ag/Pd	Scintillation	Alloy sorting	0.2% Sn*		4
Titanium	0.04–5%; 5–60% TiO_2	Rock, ore, and concentrate pulps	^{55}Fe, 1 mCi	TiK	Sc/Ti or none	Scintillation	Field assay and mine control	0.04% Ti		14, 26
	0.04–1%	Steels	^{55}Fe, 1.2 mCi	TiK	Sc/Ti or Sc/I	Scintillation	Alloy sorting	0.04% Ti	Difficult to discriminate between Ti and V with filters	4
Tungsten	0.5–20%	Steel	^{238}Pu, 20 mCi	WL	Ni/Cu	Scintillation	Alloy analysis	0.36% W*		16
	0.5–20%	Steel	^{147}Pm/Al, 0.5 Ci	WK	–	Scintillation	Alloy analysis			16
Uranium	0.001–1% U_3O_8	Ore pulps	^{109}Cd, 1 mCi	UL	Y/Zr	Scintillation	Field assay of "nonequilibrium" ores	0.006% U_3O_8		20
Vanadium	0.01–1% V_2O_5	Vanadium ores	^{55}Fe, 10 mCi	VK	Ti	Scintillation	Mine control	0.014% V_2O_5		20
	0.05–0.7%	Steels	^{55}Fe, 1.2 mCi	VK	Sc/Ti	Scintillation	Alloy sorting	0.03% V	Also see under Ti	4
	0.01–3.5%	Steels	^{55}Fe, 20 mCi	VK	Sc/Ti	Scintillation	Alloy sorting	0.01% V		16
Zinc	0.1–30%	Zinc-ore pulps	^{238}Pu, 30 mCi	ZnK	Ni/Cu	Scintillation	Field analysis	0.04% Zn; 0.17% Zn*	Interelement and particle-size effects studied	11, 13, 30
		Zinc-ore pulps	^{109}Cd	ZnK	–	–	–	–		39
	1–20%	Core samples	^{238}Pu, 30 mCi	ZnK	Ni/Cu	Scintillation	Core analysis	3% Zn*		24
Miscellaneous										
Rubber	1.5 mm thick	Flooring material	^{241}Am, 1.3 mCi	AgK	–	Scintillation	Wear measurement	±3 μm		40

*1 σ precision.

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EXPERIMENTAL SELF-LUMINOUS OVERHEAD-TYPE TRAFFIC SIGN

By Harry H. Dooley* and Jack Snyder†

The use of self-luminous products in outdoor information and direction signs has been a subject of interest to traffic engineers for many years. The U. S. Bureau of Public Roads recognized certain advantages of self-luminous overhead traffic signs over 10 years ago. However, before enriched ^{85}Kr was available, little use had been made of radioisotope-excited light sources in highway signs, primarily because of brightness limitations of the then available self-luminous sources.

Advantages of Self-Luminous Sources

Self-luminous sources offer many advantages over ordinary light sources because no electric power is required: (1) they can be used where electricity is unavailable or costly to install; (2) they are not subject to power failures or interruptions; (3) they do not burn out, and thus they provide a reliable source of light; (4) they can be used over a wide range of environmental temperatures (−100 to +170°F); (5) signs containing them need no wires or connections to the secondary power supply normally required for conventional signs.

^{85}Kr Light Sources

American Atomics Corporation (AAC) undertook in 1963, and has continued, a company-sponsored research program to develop ^{85}Kr self-luminous sources, known as I-LITES, which would have sufficient brightness for use in highway traffic signs. Since ^{85}Kr decreases in intensity only 50% every 10.6 years, self-luminous sources containing this radioisotope should have a long enough useful life to be of interest, provided the initial brightness level is sufficiently high in the optimum range.

Luminance data obtained over a 4-year period showed that a near-linear relationship exists between the brightness of the I-LITE and the ^{85}Kr content of the source. To construct light sources in the desired brightness range of 10 to 20 footlamberts (ftL), however, it was necessary to obtain ^{85}Kr gas that had been "enriched" or increased in specific activity to a level at least five to six times that of the by-product gas available from the uranium fission process.

The AEC Division of Isotopes Development has been extremely interested in seeking uses for this by-product and, in 1968, through the pilot-plant enrichment facility at the Isotopes Development Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., provided the Arizona Highway Department (AHD), through AAC, sufficiently enriched ^{85}Kr for fabrication of an experimental self-luminous overhead traffic sign.

Design—Basic Concepts

Safety is the primary factor affecting design, fabrication, installation, and use of such a device. Any

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product of this type is subject to regulatory authority—in this instance, the Arizona Atomic Energy Commission, which has licensed the AHD for use of the sign at the specified location.

The I-LITE source, whose components were selected on the basis of offering maximum integrity, was designed to withstand severe environmental conditions. The stability of this configuration is supported by over 4 years of use in a variety of applications. The phosphor used for this experimental sign has a spectral emission curve that is similar to the sensitivity curve for the eye of an average observer.

The legibility and brightness factors are based largely on Michigan State Highway Report No. R581 (Ref. 1), which indicates that: (1) legibility decreases with increasing brightness, so that 10 to 20 ftL is optimum; (2) contrast is important and is optimum at 10:1; (3) legibility under high contrast and low background is not reduced drastically, even at brightnesses as low as 1.0 ftL; and (4) various letters have differing legibility requirements. The Michiganders note further that white or light letters on a dark background are somewhat better than dark letters on a white background. Although the report refers to photometric measurements made on electrically illuminated signs, extrapolation to self-luminous performance appears very reasonable, particularly in that the Michigan sign simulator was very much like that being considered here. Further, the Michigan brightness measurements were made using the same type of instrument (Pritchard Photometer) used in our laboratory.

The Michigan tests and the experimental self-luminous sign differ in display arrangement. The AAC has used a modular approach to illumination of letters and signals as opposed to lighting the entire stroke width and height because

1. It minimizes the amount of radioisotope and hence minimizes costs while not significantly affecting legibility.
2. It offers resistance to accidental or mischievous breakage of the light modules.
3. It provides economies in construction, assembly, and replacement.

Previous visual tests at AAC have shown that the dark spacings between the modular lights do not affect legibility in the range 100 to 1000 ft, since the human eye will "group" closely spaced lights. Experiments on spacing requirements for this intended purpose have shown that the merging effect is retained up to about 3 in. separation for 1-in.-diameter sources. Moreover, a psychological effect due to vision experience will define groupings when the separation becomes a possible problem.

Construction

The direction sign is 6 ft high and 5 ft wide and has an overall weight of 750 lb. It is attached to a supporting pole capable of sustaining a threefold increase in weight, and faces in a westerly direction. The bottom of the sign is 17½ ft from the ground. The word "ONLY" is 10 in. high with 2-in. letter strokes. The arrow is approximately 34½ in. high with a 6-in. stroke. The 66 I-LITES are 1 in. in visual diameter, and each contains 1 Ci of enriched ^{85}Kr. Each light is located approximately 5 in. inward from the face of the sign and is doubly encapsulated within a metal cylindrical shell which contains a light pipe. A metal shield is placed around each light as protection against vandalism and accidents.

Performance

On July 8, 1969, the first functional, self-luminous, overhead traffic-control sign in the United States was installed in Phoenix, Ariz., by the AHD. The nominal brightness level at that time was 10 ftL. The radiation profile measurements made at that time at ground level in the immediate vicinity of the sign were slightly above background. Nighttime visibility under ambient lighting conditions of the area is in excess of 500 ft (Fig. 1).

The sign is observed monthly from ground level by AAC personnel, with periodic checks scheduled at the surface of the sign. In December 1969 such an

Fig. 1 ^{85}Kr-activated luminous highway sign in Phoenix, Ariz.

inspection of the sign surface was made. All I-LITES were functional, and no major changes in constructural integrity were found. Random photometric measurements on 27 of the lights, using portable equipment, showed an average luminous decrease for this period equivalent to approximately 7% per year. This is in substantial agreement with luminous decay data obtained using I-LITES having a nominal brightness of 1 ftL.*

Future Usage

Since the construction of the experimental sign, prototype I-LITE sources have been fabricated at brightness levels exceeding 50 ftL—i.e., five times those in the experimental sign. Widespread usage of this sign-illumination technique, however, depends largely upon the availability and cost of ^{85}Kr. The availability of this reactor by-product gas for reprocessing and enrichment is increasing rapidly and is expected to reach megacurie quantities during the next 10 years. This supply is expected also to reduce significantly the present price which, from an economic standpoint, will enhance markedly its consideration for highway-sign illumination. In addition, the commercial utilization of ^{85}Kr in this type of application will help to resolve some of the problems that arise in connection with the ultimate disposition of the radioactive by-product.

Through continuing evaluation of this experimental unit, data will be obtained on the emission spectra and changes in brightness of these light sources which have been subjected to the various environmental conditions associated with the present location. This information is needed on sources with brightnesses higher than those heretofore available in order for those involved in highway research, development, and application engineering programs to evaluate the prospective uses of ^{85}Kr-excited light sources in highway signs. (PSB)

*Note added in proof: The sign was examined again[2] on July 14, 1970, and showed no changes in the aluminum housing; no noticeable loss of anodized overcoat or paint; no visible water or moisture penetration; no evidence of discoloration, spotting, discontinuities, or cracks in any of the phosphor coatings; very slight lateral movement of 5 of the 66 I-LITE modules upon applying pressure (since each module is securely fastened within the sign structure, there is no possibility of any unit being removed). Most interesting was the fact that there was an actual increase in brightness, rather than the expected 3.8% decrease resulting from ^{85}Kr decay. This is explained by the fact that the phosphor and the photometric equipment, both of which have a positive temperature response, were ~50°F warmer in July than in December. This effect should be taken care of at the time of the proposed December 1970 inspection.

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AUTOMOBILE EXHAUST ANALYSIS FOR LEAD USING A NUCLEAR TECHNIQUE

By P. L. Sciaraffa* and C. A. Zieglert

The main source of atmospheric lead contamination is automobile exhaust. Recently, increasing interest has been shown in a convenient method of measuring the level of lead in the atmosphere. Because of this interest, an investigation was made of the feasibility of sampling the atmosphere with a Millipore filter and then using a radioisotope-excited X-ray-fluorescence analyzer to determine the amount of lead collected.

The purpose of this study was threefold: (1) to show the feasibility of collecting samples on a Millipore filter and doing elemental analysis by X-ray fluorescence, (2) to establish working calibration charts for the Panalyzer-4000,‡ and (3) to determine the minimum quantity of lead detectable with the instrument.

Instrument Design and Operation

The instrument consists of a probe and an electronic console. The probe contains a radioactive source that is constructed so as to emit radiation only in the direction of the sample, i.e., the particles collected on the Millipore filter. Radiation striking the sample causes some of its atoms to emit X rays of an energy characteristic of the emitting element. These characteristic X rays pass through the window of an X-ray

*Millipore Corp., Bedford, Mass. 01730.
†Panametrics, Inc., Waltham, Mass. 02154.

‡Manufactured by Panametrics, Inc., Waltham, Mass. 02154.

detector; the detector can resolve X-ray energies, producing as an output a voltage pulse. Voltage pulses from the detector are introduced into the electronic console where they are sorted and counted for a preset measurement time, and the number of pulses is displayed digitally on the console. This number is then used in conjunction with a calibration chart to obtain the amount of the measured element in the sample. Typical measurement times are of the order of 1 min.

In the design of the probe, provision has been made for the use of the difference-filter technique to cancel out background radiation. Whether or not filters are required depends on the application and the accuracy desired. That is, the instrument is designed so that it will either count up (i.e., add) or count down (i.e., subtract). Thus it can be used in applications requiring (1) no filter, (2) a single filter, or (3) balanced-difference filters. In either of the first two cases, it is only necessary to "count up" for a determination. In the latter case the first of the difference filters is selected so that it transmits both the background and the desired X-ray signal, and the second so that it transmits the background preferentially. The filters are balanced so that they transmit equal background intensities.

Sample Collection

The X-ray-fluorescence technique is feasible where airborne lead concentrations are such that a sufficient sample can be collected in a reasonable time. Typically, in urban areas air-sampling times of 6 to 12 hr provide enough lead sample to allow measurement.

The Millipore filter acts as a two-dimensional screen; it readily removes and retains on its surface all airborne particles larger than the specified pore size. Using 47-mm type AA filters (0.8-μ pore size) and the standard Millipore aerosol holder, samples were collected in various locations and for various lengths of time.

Analyses

The samples were analyzed by X-ray fluorescence using the Panalyzer-4000. The advantages of this radioisotope method are that wet chemistry is not required and rapid results are obtained using low-cost portable equipment. The procedure, using the Panalyzer-4000, is to "count up" with the first filter and then to "count down" for the same length of time with the second filter, thus subtracting the background and leaving only the desired signal counted and displayed. It should be noted that, because this technique is nondestructive, several elements can be determined from one sample. Also, after determination by X-ray fluorescence, the sample is available for other tests.

Since the instrument depends on X-radiation originating in the atoms of the sample, it is desirable that the particles be on a surface, as is true of a sample collected on a screen filter. Radiation from particles within the matrix of a depth filter may not reach the detector and thus may not be counted.

The L-lines of lead were excited by a ^{109}Cd source, and a 64-sec counting time was used. Both qualitative and quantitative analyses are possible. A number of elements were detected qualitatively, most notably bromine and lead. Since ethylene dibromide is added to gasoline to remove lead from automobile engines, the lead in the exhaust is expelled mostly as lead bromide, $PbBr_2$.

Calibrations

Calibration charts (showing counts recorded vs. amount of element sought) were established by collecting the samples, counting the samples on the Panalyzer-4000, and then having the samples analyzed for lead by independent laboratories using atomic absorption. However, it was soon obvious that the bromine fluorescence overlapped a portion of the fluorescence due to lead. To get around the problem of the bromine, two methods were tried and both gave consistent results. The first, and simpler, method is to make the assumption that the Pb/Br ratio is constant; this assumption can be tested, for purposes of establishing a calibration chart, by chemical analysis. The second is to use the filters. This method excludes all the fluorescence due to bromine; it also excludes part of the fluorescence due to lead. The result is a count due only to lead. Unfortunately this technique also results in decreased sensitivity. Thus, while it is possible to detect 5 μg of lead without the filters on this instrument, the minimum detectable amount of lead with the filters in place is more like 15 to 20 μg.

(PSB)

MINIMIZING ERRORS IN GAMMA-RAY BACKSCATTER DENSITY GAGES: EXISTING GAGES AND NEW DESIGN CONCEPTS*

By F. H. McDougall and W. L. Dunn†

Gamma-ray backscatter-type soil-density gages have been in existence for a decade but have been plagued by calibration and accuracy problems. Before these devices can gain more widespread acceptance, their accuracy must be improved. A project sponsored by the Highway Research Board has been undertaken to evaluate new design concepts for improving these nuclear devices. Two prototype systems were designed to accomplish the project's objectives—one similar in design to existing commercial gages and another utilizing gamma-ray spectrometry, a more sophisticated approach.

Gage Errors

A dual-gage principle involving the simultaneous solution of calibration models for the two gages was developed by Gardner and Roberts[1] and has been used to define and evaluate three gage errors: composition, measurement of counting rate, and surface roughness. The dual-gage principle was designed to minimize composition error, which it does successfully. The other two errors can be minimized by an optimization procedure which evaluates gage performance through the use of a quality factor which, in turn, is a function of the three gage errors and the sample volume measured. The quality factor is studied as various gage design parameters are varied. Work is also continuing in search of a mathematical model that would be used to eliminate the surface-roughness error, probably the most serious of the three.

Gage Systems

One of the prototype gage systems uses a Geiger-Müller (G-M) tube detector and is concerned with the variation of the following gage parameters: source energy, source collimation length, source–detector separation, and detector efficiency spectrum. Results of initial testing with the system are promising and indicate that the three gage errors can each be reduced to about 1 lb/ft^3 or less simultaneously for a proper combination of the design parameters. The best dual-gage system in the initial study uses a ^{60}Co source, a source collimation length of $\frac{5}{8}$ in., and both a Harshaw G 17-6 G–M tube and an identical tube except for a 10 mg/cm^2 platinum coating on its inner wall at source–detector separations of 4 and 10 in., respectively.

The new design factors of the gamma-ray spectrometry prototype system permit varying source and detector collimation, angle of source and detector incidence into the soil, and energy regions being detected. These new design factors are used in conjunction with the existing basic parameters: source energy and intensity, source–detector separation, and detector type. The prototype utilizes the spectrometric capabilities of a NaI(Tl) crystal detector and a multichannel analyzer system. Mathematical modeling appears to be a promising tool for further reduction of the surface-effect error.

Results

Preliminary results indicate that significant advantages are realized in combining the various gage design factors in an optimum manner. Considerable improvement over existing commercial gages is noted. (PSB)

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1. R. P. Gardner and K. F. Roberts, Density and Moisture Content Measurement by Nuclear Method, NCHRP Report 43, 1967.

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*The actual paper appears in Highway Research Record No. 301 (Spring 1970).

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Potential Industrial Applications of the ^{57}Fe Mössbauer Effect*

By J. H. Terrell†

Supplementary Keywords: *industry; industry, primary metal; metallurgy, ferrous; physical property; Mössbauer effect; absorptiometry; spectrometry; review, technical; backscatter; theory, applied; comparison; molecular structure; crystal; differentiation; carbon; chromium; zinc; cobalt-57; iron-57.*

Abstract: *The application of the Mössbauer-effect technique to several industrially significant problems is discussed; iron-bearing materials are emphasized. A review is given of past results and of current efforts to conduct Mössbauer-effect measurements that use the 2% naturally abundant ^{57}Fe isotope and that do not require sample preparation, i.e., backscatter rather than transmission measurements. Detection schemes in the backscatter geometry that use 6.3-keV internal-conversion X rays, 14.4-keV gamma rays, or 8-keV internal-conversion electrons are compared. Potential applications of the backscatter technique to metallurgical problems are summarized; they include studies of the typing of metals, thermomechanical history, magnetic properties, corrosion products, surface-hardening processes, and metallic coatings. Preliminary results obtained with the backscatter method on a steel coupon in axial tension are included. Other industrial applications that are accomplished best with transmission geometry are also summarized.*

Since the discovery of the Mössbauer effect in 1957, it has been possible to probe the microstructure of materials in new and meaningful ways. The complex instrumentation and the specialized sample preparation needed have made Mössbauer-effect measurement almost exclusively a laboratory technique. Minimal attention has been paid to the possibility of making practical use of the effect for nondestructive testing and other applications.

In the earth's composition iron is one of the most abundant elements. It constitutes ~5 wt.% of the continental crust and ~7 wt.% of the entire crust. Furthermore, it is so widely distributed that few natural solid materials are without it. Among the principal elements of the earth's crust, iron is exceptional in that it commonly exists in two valence forms and passes relatively easily from one to the other as the result of oxidation or reduction. The ^{57}Fe isotope is 2% naturally abundant. It appears that enough ^{57}Fe Mössbauer-effect data have been accumulated to permit serious consideration of its potential industrial applications. The discussion that follows is based on work done at Sanders Associates and at other laboratories. Some of the results are preliminary and exploratory.

PRINCIPLE OF THE MÖSSBAUER EFFECT

The Mössbauer effect is the recoilless emission and reabsorption of a low-energy gamma ray by a nucleus embedded in a solid. Figure 1 depicts a gamma-emitting nucleus embedded in an atom that is in free space. On an energy scale, the energy of the gamma ray as it leaves the nucleus is designated by E_0, and its energy after it leaves the nucleus is denoted by $E_0 - R$, R being the recoil energy of the nucleus. Thus the energy of the gamma after it leaves a nucleus that can recoil is diminished by the imprecisely defined amount R, as shown in Fig. 1. When a gamma ray is emitted from a nucleus embedded in a crystalline solid, E_0 is well defined because emission occurs without recoil and R is therefore negligible.

The principle of resonant absorption is illustrated at the bottom of Fig. 1 by the superimposed emission and absorption lines. The equation indicates that R can be made very, very small if the mass of the solid, M, is large enough. This result follows from the conservation of energy and momentum. Thus it can be considered that R is reduced by an amount inversely proportional to M. This recoilless emission and reabsorption of a low-energy gamma ray by a nucleus in a solid is the Mössbauer effect. The last equation on Fig. 1 implies that E_0 may be varied by Doppler-shifting either the source or the absorber at relative velocity, v, with respect to the other; the magnitude of v is of the order of millimeters per second.

The hardness, dimensional stability, strain aging, and stress-corrosion cracking of iron alloys have been determined by observing the metallurgical phase changes involved. X-ray and electron diffraction, re-

*Work supported jointly by Naval Air Systems Command and Sanders Associates, Inc.

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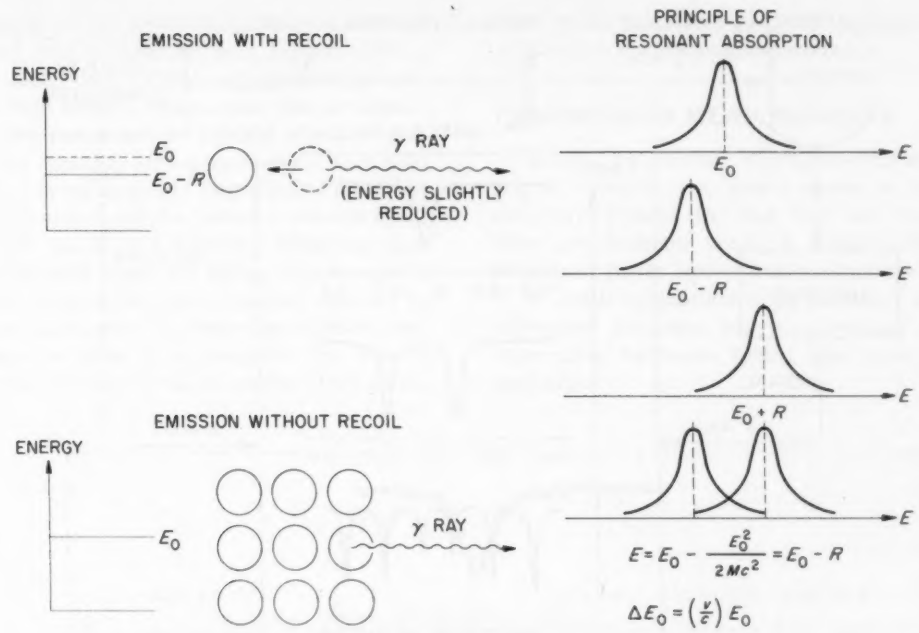

Fig. 1 Recoilless emission and reabsorption of low-energy gamma rays of nuclei embedded in solids.

sistometry, and internal-friction techniques have traditionally been used to follow the phase changes. Transmission Mössbauer-effect measurements have recently been used to study some of these properties, but, as in the X-ray- and electron-diffraction methods, sample preparation is needed to obtain useful results. However, in the backscatter Mössbauer method, sample preparation is not necessary. The specimen need not be "touched" except by the Mössbauer gamma rays. Therefore backscatter measurements, as compared with transmission measurements, give a more realistic picture of metallurgical processes that occur in and near the surface of iron alloys, inasmuch as sample preparation can introduce unwanted—and sometimes unknown—effects.

INSTRUMENTATION

A block diagram of the instrumentation for transmission Mössbauer spectrometry is given in Fig. 2. The radioactive source is driven back and forth by a velocity transducer; the gamma rays from the source pass through a thin sample and impinge on a detector. It is convenient to display the number of counts detected vs. the velocity of the transducer as an x–y plot; a multichannel scaler performs this function. The top spectrum contains a single inverted peak, which is indicative of ^{57}Fe nuclei that are present in cubic environments. The middle spectrum shows two inverted peaks, which are characteristic of ^{57}Fe nuclei that are present in a noncubic environment. The bottom spectrum shows six inverted peaks, which indicate that the ^{57}Fe is in a magnetic state. The spectrums are called "fingerprints" because they indicate unique features about the physical state of the iron embedded in the solid. In addition, each spectrum gives information on the chemical state of the iron, which is measured by the shift of the center of gravity of the spectrum away from the zero-velocity point. Note that the transmission geometry requires thin samples (1 to 10 mils thick).

Figure 3 shows the configuration of a backscatter (reflection) Mössbauer spectrometer. In the backscatter Mössbauer spectrometer, the reflected 6-keV internal-conversion X rays, 14-keV gamma rays, or 8-keV internal-conversion electrons are counted as the velocity of an emitter (^{57}Co) relative to that of an absorber is varied. The Mössbauer spectrometer is a "spectrometer" because the precise energy of emitted or absorbed radiation depends on the chemical environment, local electric-field gradient, and local magnetic field at the emitting or absorbing nucleus. The velocity

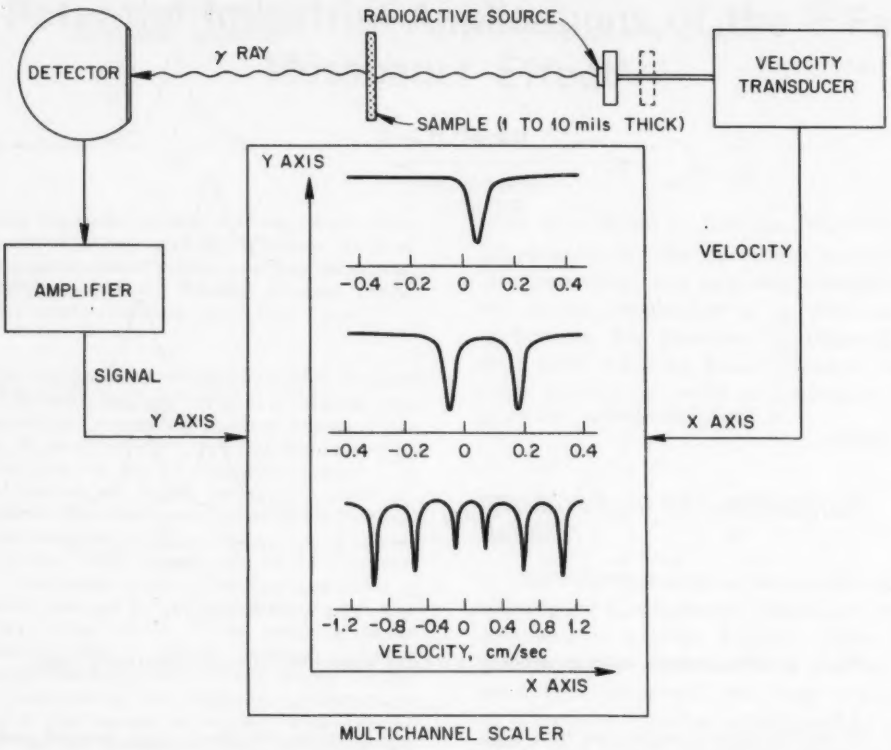

Fig. 2 Block diagram of instrumentation for transmission Mössbauer spectrometry.

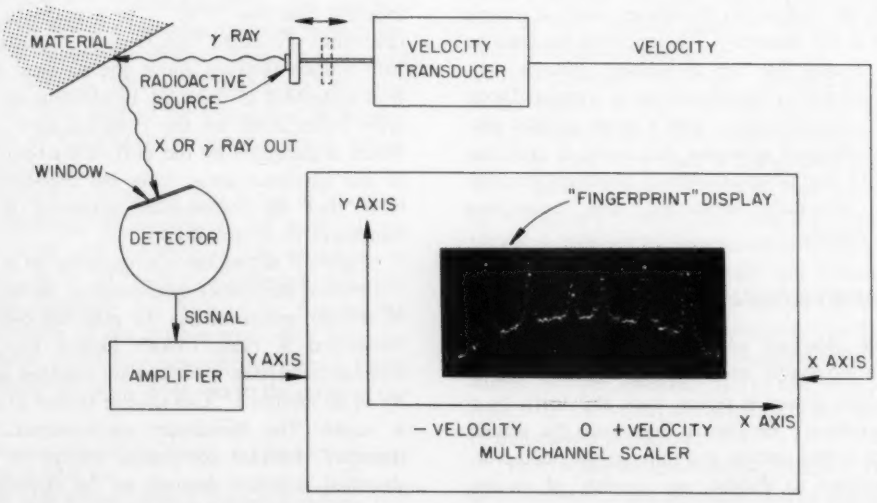

Fig. 3 Block diagram of instrumentation for backscatter (reflection) Mössbauer spectrometry.

of the emitter relative to that of the absorber serves to bring them into coincidence via a Doppler shift, a necessary task when emitter and absorber are not identical. Thin samples, which require special preparation, are not needed, and the backscatter produced by gamma rays impinging on a semi-infinitely thick solid are detected as indicated. For naturally abundant ^{57}Fe it is convenient to count the internal-conversion 6-keV X rays that are emitted following Mössbauer-effect events in the solid. Again, the display as an $x-y$ plot is useful. The six-peak fingerprint spectrum obtained by use of the backscatter Mössbauer spectrometer indicates that the material is magnetic; the distance between the outermost peaks shows that it is a ferritic steel. In the backscatter spectrum the peaks are not inverted as in the transmission spectrum.

TRANSMISSION MEASUREMENTS

Typical transmission Mössbauer-effect spectrums (Fig. 4) illustrate that various phases of steel give characteristic peaks. The data from cast iron (Fig. 5) show how cementite (Fe_3C) is readily distinguished from ferrite (under separated six-peak spectrum).

In certain applications of the Mössbauer effect, the backscatter technique has no advantage over the transmission technique. Table 1 gives some of these applications.

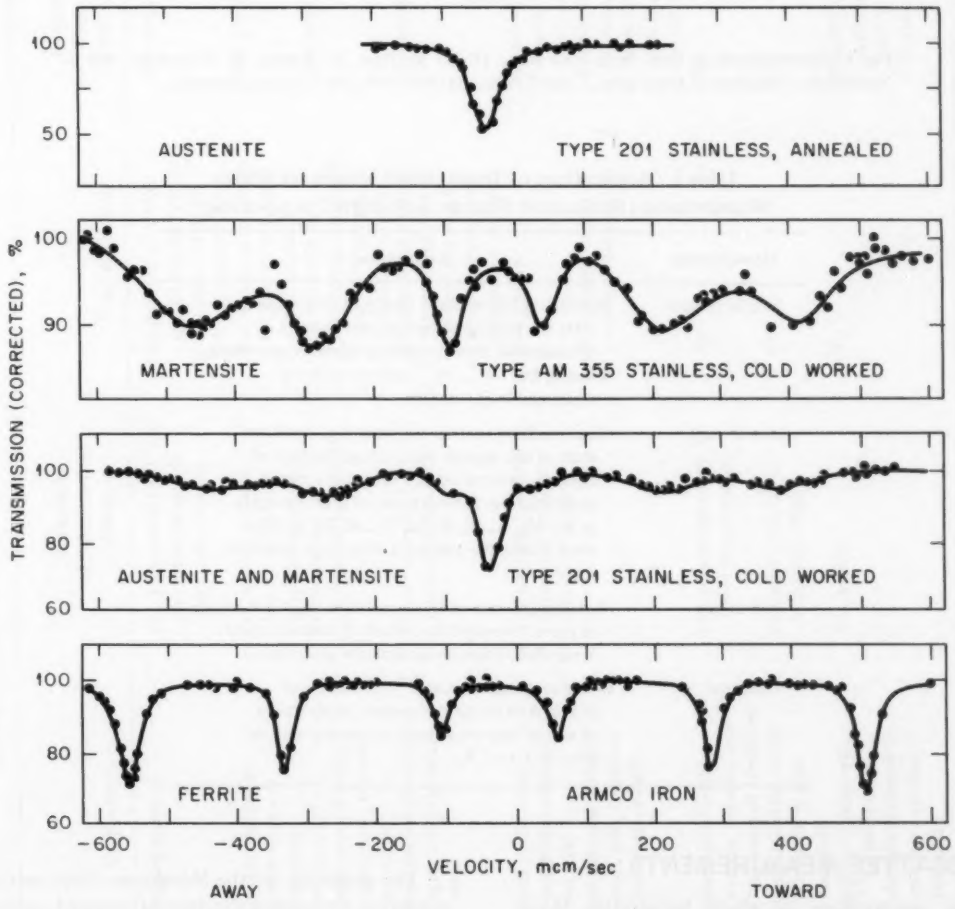

Fig. 4 Transmission Mössbauer-effect spectrums of various types of stainless steel and iron. [From C. W. Kocher, The Iron-57 Mössbauer Effect in Some Stainless Steels, *Phys. Lett.*, 14: 287-289 (1965); with permission.]

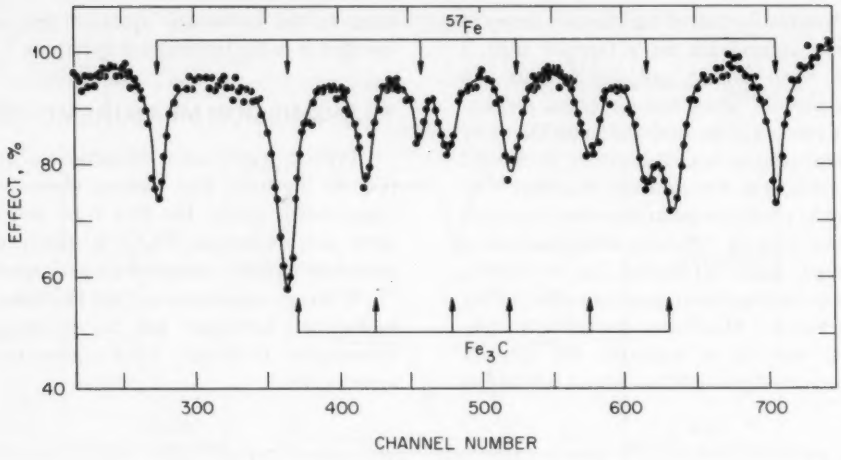

Fig. 5 Mössbauer-effect data from cast iron. [From M. Ron, A. Kidron, H. Schechter, and S. Niedzwiedz, Structure of Martensite, *J. Appl. Phys.*, 38: 590-594 (1967); with permission.]

Table 1 Applications of Transmission Mössbauer-Effect Measurements (Backscatter Measurements Have No Advantage)

Measurement	Application
Iron in cement	Monitoring the reaction that goes to completion after the mixing of cement and water, i.e., hydration of iron-containing clinker components. Relating the Fe^{2+}: Fe^{3+} ratio to color of white and buff cements.
Iron in coal	Characterizing nonmineral iron, e.g., the ionic state of the organic iron. (Identification of minerals present usually does not account quantitatively for existence of such elements as Na, Mg, Al, Si, K, Ca, Ti, and Fe. In this work a hitherto-unknown Mössbauer spectrum was found.)
Iron in slag	Identifying forms of iron present in slag from engines or pipes. (Amorphous nature of material makes X-ray-diffraction measurements inaccurate.)
Vibration	In biomechanics a small ^{57}Co source was attached to an ear tympanum. Amplitudes of several angstroms were measured with an error of 1 to 2 Å.

BACKSCATTER MEASUREMENTS

Some applications in which backscatter Mössbauer-effect measurements are considered to be potentially suitable are given in Table 2. Discussions of specific applications follow.

The suitability of the Mössbauer-effect method for measuring the volume fraction of retained austenite in steel specimens has been demonstrated by Chow and Bogner;[1] for this measurement the backscatter technique is accurate and requires no sample preparation.

Table 2 Applicability of Backscatter Mössbauer-Effect Technique: Comparison with Other Techniques

Application	Backscatter Mössbauer-effect technique	X-ray diffraction	Radioisotope X-ray fluorescence and X-ray spectrography	Magnetic technique (e.g., saturation magnetization)
Stained austenite	Yes; presence of Fe_3C can[6] give error; no sample preparation needed	Possible but only with special sample preparation; error same as for Mössbauer effect	Not possible	Gross effect and not quantitative
Carbon content in martensite and austenite	Yes; error not exactly[11,12] known; no sample preparation needed	Yes; sample preparation needed, since texture can affect results	Not possible	Yes; not accurate
Identification of steel types (ferrite, martensite, austenite, cementite)	Yes; no sample[7-9,14] preparation needed	Yes, but preferred orientation and broad lines make sample preparation necessary	Not possible	Questionable
Precipitation due to aging and heat-treatment	Yes; no sample[4,5,10,13] preparation needed	Not possible in martensite with high carbon content; possible in austenite but sample preparation required	Not possible	Not possible
Quality control of nonferrous coatings on steel	Yes; to study bonding properties down to depths of 2 mils	Not possible	Could be used to give coating depth but no structural information	Not possible
Dry chemical analysis (e.g., ores, corrosion products on steel)	Yes	Not possible except with powder patterns	Specific elements monitored but no identification of chemical compounds possible	No
Detection of relative motion, velocity, and frequency of vibrations	Yes; amplitudes of 10 Å have been measured[2]	No	No	No
Monitor ductile–brittle transition in stainless steels	In research stage;[3] looks promising	No	No	No
Marking of parts with ^{57}Fe isotope for ablation studies or to monitor corrosion formation	Yes; unique	No	Possible if a radioactive isotope with useful half-life is used	No

The backscatter spectrum of tool steel (Fig. 6) is characterized by the structure in the central portion of the spectrum. With increase in the chromium content of such a steel, the velocity shift of the centroid of the

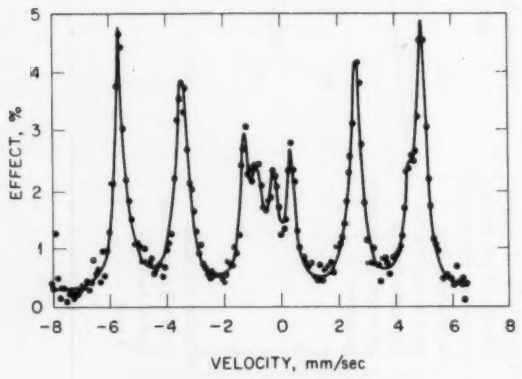

Fig. 6 Backscatter Mössbauer spectrum of tool steel (Fe, 85.5%; Cr, 12%; C, 1.5%; Mo, 1%).

spectrum (isomer shift) varies (Fig. 7). In Fe–Cr alloys, the maximum of the isomer shift occurs at about the same composition as that at which the alloy softens. The separation between the outermost peaks (hyperfine field) in the six-peak spectrum of a martensite steel varies with carbon content (Fig. 8); the solid line is the X-ray-diffraction result. Carbon concentrations <0.5 wt.% approach the limit of resolution.

Figure 9 shows the backscatter Mössbauer-effect spectrum of as-machined 52100 bearing steel and also the spectrum of the steel after it was given a normal heat-treatment. The appearance of the central peak for the heat-treated sample permits measurement of the effect of the heat-treatment. This peak is characteristic of many heat-treated martensite steels and can be related to their magnetic properties acquired as a result of the heat-treatment. The backscatter spectrum of a Simonds-81 hysteresis sample (Fig. 10) also illustrates the heat-treatment effect. The amplitude of the additional peak in the center of the spectrum is related directly to the squareness of the hysteresis loop of this material. Thus the amplitude of the peak can indicate the mechanical integrity and the magnetic quality of steels.

The backscatter Mössbauer effect can be used to detect compound formation on a steel surface without sample preparation (Fig. 11). The spectrum at the top of Fig. 11 is of a rusted steel plate. After the rust was

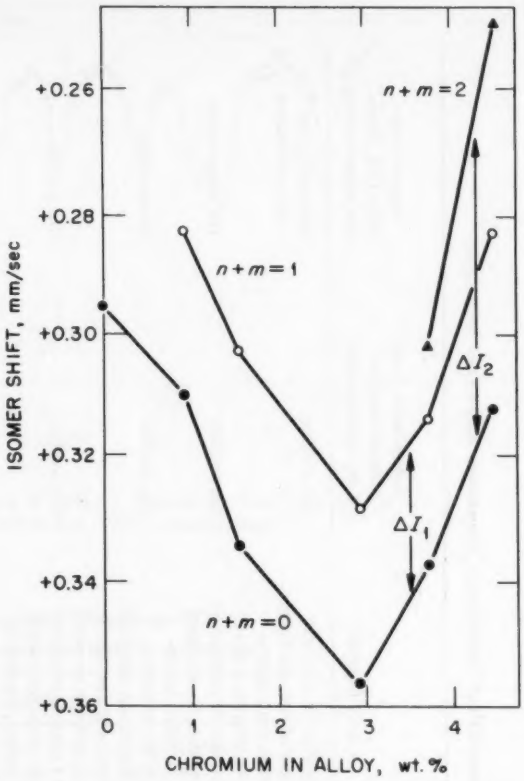

Fig. 7 Isomer shift observed in Fe–Cr alloys as a function of composition and number of chromium neighbors; n and m = number of chromium near and next-near neighbors, respectively, and ΔI_1 and ΔI_2 = isomer shift observed with an increase of 1 and of 2, respectively, in chromium neighbors (data are plotted relative to the centroid of the absorption spectrum of sodium nitroprusside at 300°K). [From W. E. Sauer and R. J. Reynik, Solid-Solution Strengthening in Fe–Cr Alloys Using Mössbauer Spectroscopy, in *Mössbauer Effect Methodology*, I. J. Gruverman (Ed.), Vol. 4, pp. 201-214, Plenum Press, New York, 1968; with permission.]

removed in two successive steps, the next two spectrums were obtained. The double-peaked pattern was identified as being typical of β-ferrioxyhydroxide, whose Mössbauer-effect parameters are given in Table 3. These parameters of iron oxides and iron oxyhydroxides can be described uniquely by the values of their chemical (or isomer) shifts, quadrupole splitting (spectrum between double peaks), and internal magnetic or hyperfine field (i.e., if there is a six-peak pattern). The measurement of values for these parameters proved that the "rust" actually was β-ferri-

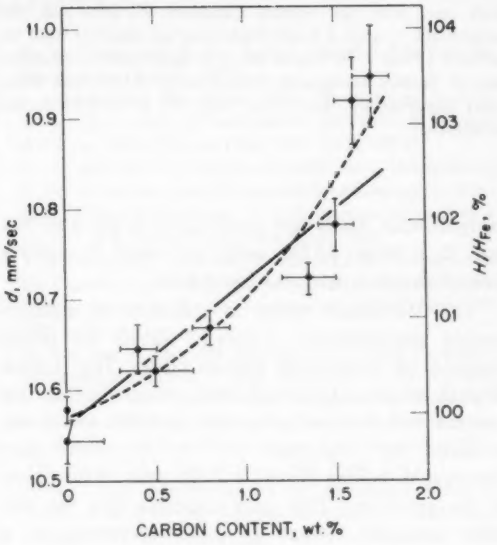

Fig. 8 Hyperfine field in martensite vs. carbon content (d = distance between outermost peaks; H = hyperfine field of martensite; H_{Fe} = hyperfine field of pure iron). [From T. Zemcik, Mössbauer Measurement of Hyperfine Field in Martensite, *Phys. Lett., A*, 24: 148-150 (1967); with permission.]

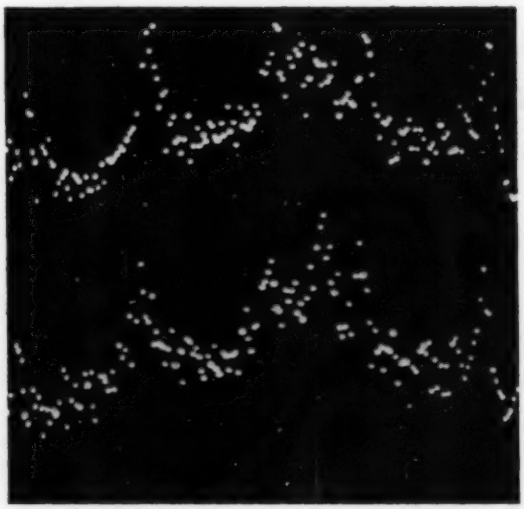

Fig. 9 Innerrace of 52100 bearing steel as-machined (upper) and after normal heat-treatment (lower).

Fig. 10 Central portion of backscatter Mössbauer spectrums of Simonds-81 hysteresis material as-received (lower) and after heat-treatment (upper).

Table 3 Mössbauer Parameters of Iron Oxides and Iron Oxyhydroxides at 300°K*

Compound	Chemical shift,† mm/sec	Quadrupole split, mm/sec	Internal magnetic field, kOe	Ref.
FeO	1.37	0.6	0	15
α-Fe_2O_3	0.61	0.40	517 ± 5	16
γ-Fe_2O_3				
Td site	0.53§ ± 0.04	0	488 ± 5	17
Oh site	0.67§ ± 0.04	0	499 ± 5	
α-FeOOH	0.70§	0 ± 0.1	364 ± 37	18
β-FeOOH	0.640 ± 0.006	0.700 ± 0.008	0	19
	-	-	475 ± 5†	20
γ-FeOOH	0.648 ± 0.006	0.594 ± 0.006	0	19
δ-FeOOH	0.76 ± 0.2	0 ± 0.1	0	20
Td site‡	-	-	525 ± 5	
Oh site‡	-	-	505 ± 5	

*From J. H. Terrell and J. J. Spijkerman, Determination of Surface Compound Formation by Backscatter Mössbauer Spectroscopy, *Appl. Phys. Lett.*, 13: 11-13 (1968); with permission.

†Chemical shift relative to sodium nitroprusside standard.

‡Values are for 77°K.

§Corrected, by adding 0.17 mm/sec, to sodium nitroprusside standard.

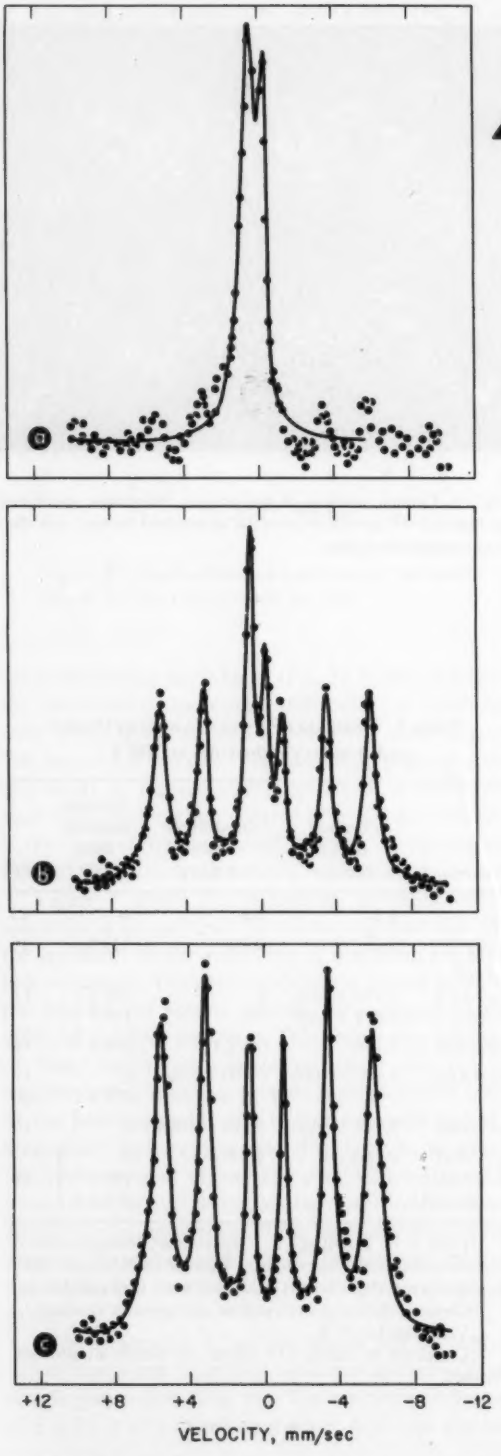

Fig. 11 Backscatter Mössbauer spectrums of a rusted $\frac{1}{8}$-in.-thick steel plate (*a*, original condition; *b*, after rust was scraped off; *c*, after a 1-mm-thick layer was removed from the surface). [From J. H. Terrell and J. J. Spijkerman, Determination of Surface Compound Formation by Backscatter Mössbauer Spectroscopy, *Appl. Phys. Lett.*, 13: 11-13 (1968); with permission.]

oxyhydroxide. Such data can be used in the same way that data from ASTM cards are used to analyze X-ray-diffraction patterns of powders.

The Mössbauer effect is indicative of metallic-coating characteristics. Figure 12 shows the results obtained on zinc-coated turbine blades. The familiar six-peak spectrum (*a*) was derived essentially from the base material. Increasing the zinc thickness to 1.2 mils produced the fingerprint (*b*); the six peaks have disappeared, leaving instead a single peak in the center of the spectrum. This peak indicates that the iron either occupies centers of cubic symmetry or is randomly situated in the lattice. The only region of the sample that could be responsible for this behavior is the diffusion-bonded intermetallic zone. Thus the backscatter Mössbauer technique can provide, nondestructively, metallurgical information about the intermetallic region without sample preparation.

(HPR)

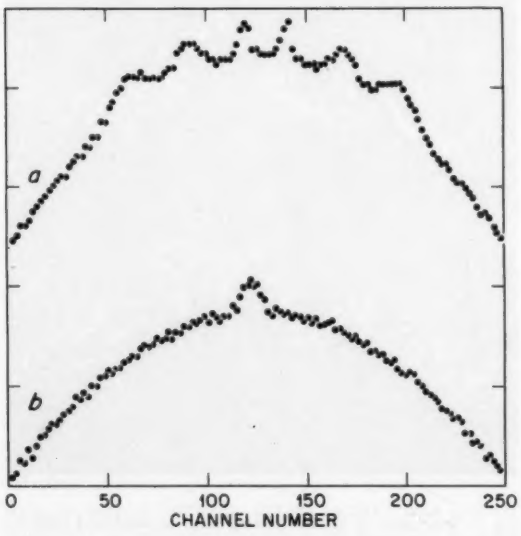

Fig. 12 Backscatter Mössbauer spectrums of zinc-coated turbine blades (*a*, 0.2-mil coating; *b*, 1.2-mil coating).

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Neutron Activation Analysis in Oceanography: International Symposium

Supplementary Keywords: *activation, neutron; source, bremsstrahlung; reactor; generator; chemistry, analytical; chemistry, inorganic; biology; ecology; geology; geophysics; oceanology; sedimentology; industry; industry, nuclear energy; tracer; material tracing; water and waste treatment; safety; radiochemistry; radiolysis; separation, physical process; chromatography; spectrometry; luminescence; secondary radiation effect; solvent extraction; sorption; ion exchange; precipitation; counting; conference; bibliography; data handling; facility description; pollution; comparison; sea; worldwide; Belgium; France; Germany; England; Italy; Monaco; Norway; semiconductor; fallout.*

Abstract. *The NATO Subcommittee on Oceanographic Research sponsored the International Symposium on the Application of Neutron Activation Analysis in Oceanography held at the Royal Institute of Natural Sciences of Belgium, Brussels, June 17–22, 1968.* Thirteen participants from eight countries presented 12 papers. The symposium is summarized briefly, and the papers presented are listed.*

In his inaugural speech, the chairman of the symposium, Professor A. Capart, Royal Institute of Natural Sciences of Belgium, pointed out that the characterization of oceanic regions no longer depends on the laborious measurement of their temperature and salinity. The determinants are likely the presence or the absence of certain oligelements. In the scope of

*NATO Subcommittee on Oceanographic Research, *International Symposium on the Application of Neutron Activation Analysis in Oceanography*, Institut Royal des Sciences Naturelles de Belgique, Bruxelles, Juin 1968.

oceanographic research, he believes that there are three important problems without sufficient data: the energetic exchange between "air and sea," the oceans' productivity of nutrients, and sea pollution. As an oceanographer, he expects neutron activation analysis to provide a fingerprint of each oceanic mass and to answer previously unanswered questions.

The papers presented reiterate the need for great care in taking and preserving samples so as to ensure that the results of their analysis will indicate correctly their initial compositions. Neutron activation analysis is shown to be sufficiently sensitive to measure the oceans' trace elements without prior concentration of samples. The technique, used together with neutron generators and on-line computers, permits the handling of the great quantity of results needed to study the innumerable phenomena involved in the interaction between life and chemical elements in the sea—an interaction that starts with the radiant energy of the sun and continues to the bottom of the ocean. Concurrent studies of natural and artificial radioisotopes and of stable elements and their radioactive counterparts are shown to be highly valuable in these fundamental investigations in oceanography.

INORGANIC CHEMISTRY OF THE OCEAN

In the single paper on the subject, Goldberg[1] assigned three characteristics to the inorganic chemical reactions in the ocean: (1) the reactants are in micromolar or submicromolar concentrations; (2) the time constants of the reaction rates are in units of thousands, tens of thousands, or hundreds of thousands of years or more; and (3) the reactions occur at the interfaces between geologic domains—the sediment–hydrosphere, the hydrosphere–biosphere, and the hydrosphere–atmosphere. He discussed how these reactions may be understood from knowledge of the concentrations and speciations of the reactants, from mineralogical and chemical studies of the products, and from the properties of the reaction sites.

ACTIVATION ANALYSIS OF SEAWATER, MARINE ORGANISMS, AND MARINE SEDIMENTS

Because activation analysis is not yet a seagoing technique, samples from the sea must be preserved for a certain period of time. The problems of proper sampling and of pretreatment before the irradiation were discussed by Fukai.[2] He considered pretreatment procedures, such as phase separations and chemical separations, from a general point of view and discussed briefly the separations of organically bound fractions of trace elements and the chemical-reaction rates of trace elements in extremely small concentrations in seawater. He emphasized the need to cross-check the results of various methods of analysis and suggested that the neutron activation technique may serve as a reference and permit the adoption of procedures that are free of reagent blanks.

The rates of introduction of radioactivity into the marine environment must be so adjusted as to ensure that the rates of return of radioactivity to man, and the consequential human radiation dose rates, do not exceed those deemed acceptable. Preston and Dutton[3] used neutron activation analysis in studies of marine radioactive pollution. They studied the cycling of trace elements in United Kingdom coastal and shelf waters already contaminated by radioactive effluents. Their study has particular relevance in predicting the environmental consequences of the use of nuclear explosives or the contamination resulting from waste-disposal operations. They reviewed the use of neutron activation and atomic absorption spectrophotometry for the determination of traces of selected metallic elements in multicompartment concentration processes typical of United Kingdom coastal waters. They compared the behavior of stable and radioactive nuclides and their change with distance from disposal area and with time.

Over a 3-year period, Hødgahl[4] studied the distribution of lanthanides in seawater. He presented the results of some 40 to 50 analyses, discussed the results in relation to seawater masses, and gave a tentative explanation of the observed distributions.

At their institute, in the Activation Laboratory built for the purpose of determining trace and oligelements in seawater and marine organisms, Peeters and Lacroix[5] analyzed samples from the North and Mediterranean Seas, brought back from their expedition in August 1967 on board the oceanographic vessel "The Charcot." Without using chemical separation, they were able to determine more than 20 elements. They presented gamma-ray spectrums of four samples, including surface- and deep-water samples. They discussed the problems of sampling without contamination and of obtaining quartz sufficiently pure for use as irradiation capsules. With the objective of "fingerprinting" each type of sea or ocean and correlating its types of flora and fauna with the composition of their environment, they showed how the results of their first experiments justified their plan to acquire a multiprogramming computer and a neutron generator.

The marine biosphere must be included in any comprehensive study of the oceans' trace elements, because biological assimilation is an important mechanism that affects the concentrations and behaviors of many trace elements in the marine environment. In a more broad-based study, Robertson, Rancitelli, and Perkins[6] measured the concentrations of numerous trace elements in seawater, marine organisms, and pelagic sediments. They counted neutron-activated samples directly on either a multidimensional gamma-ray spectrometer or a large-volume high-resolution Ge(Li) diode spectrometer after optimized decay periods. They thus measured the concentrations of the trace elements Sr, Cs, U, Co, Sb, Zn, Fe, and Sc in seawater samples and their distribution over a wide geographical area of the Pacific and Atlantic Oceans. The concentrations of Zn, Co, Ag, Cs, Sb, and Sc were measured in a large number of surface, midwater, and benthic marine organisms from various trophic levels. The additional elements Na, K, Rb, Br, Fe, Se, and Hg were also measured in tissue samples from silver salmon and Alaskan king salmon. The elements Mn, Fe, Cu, Zn, Co, La, Sc, and Sb were measured in pelagic sediments and in manganese nodules by directly counting neutron-activated samples on a multidimensional gamma-ray spectrometer. With a Ge(Li) diode detector and properly selected irradiation and decay periods, they also measured the additional elements Al, V, Dy, Ba, Cr, Ce, Sm, Yb, Lu, Hf, and Th in sediment samples by direct counting. The direct-counting methods greatly simplified the multielement analysis of samples from the marine environment by eliminating the uncertainties associated with many complex chemical preconcentration and separation procedures. Also, the inherent risk of contamination of the samples during such procedures was eliminated. The behavior of several artificial radioelements entering the marine environment as fallout, relative to their stable-element counterparts, was determined and points out the importance of chemical or physical form on the behavior of an element in the ocean. Robertson described methods for extracting trace radionuclides from large volumes of seawater to depths as great as 1600 m.

Studies of the marine biosphere were described by Merlini[7] also. She pointed out that the interest in the amounts and distribution of stable elements in aquatic organisms has increased with the recognition that such information is important as a guide and measure of the levels that radioisotopes, introduced as contaminants, might attain at the equilibrium state. She described the determination by neutron activation analysis of five elements (Co, Cs, Mn, Sc, and Zn) over a period of 1 year in fishes, macrophytes (water plants), mollusks, and the water of Lake Maggiore, north Italy. She compared her results with results reported in the literature for the same elements in seawater and marine organisms. She concluded that activation analysis is an excellent tool for obtaining information that is especially useful to biologists, who are faced with many badgering problems related to radiocontamination of environments, especially aquatic.

The usefulness of neutron activation analysis in the different branches of radioecology was discussed by Feldt.[8] He presented results of determinations of six elements (Co, Cu, Fe, Mn, Mo, and Zn) in deep-sea organisms. The difficulties of sampling and storage were also considered. The facilities of the new Activation Laboratory of the German Board of Fisheries Research were described.

Activation-analysis techniques used by Boudin and associates[9] in geology and glaciology are also useful in oceanography. Boudin described the advantages of the techniques, based on detection of short-half-life nuclides, for the determination of lutetium, zirconium, and hafnium in oceanographic samples. Low contamination levels were achieved by the storage and irradiation of samples in the frozen state and the use of specially tested clean material in dust-free laboratories. The activation-analysis results were compared with those obtained by atomic absorption and isotope dilution.

No copy of the paper presented by Chesselet[10] was made available for inclusion with the symposium papers, nor was an abstract.

POTENTIAL OF NEW FACILITIES AND COMPUTER TECHNIQUES IN OCEANOGRAPHY

Two papers described the potential of new facilities and computer techniques in oceanography but did not give results of the analysis of oceanographic samples.

The activation-analysis laboratory of the Euratom Research Center at Ispra, Italy, was described by Girardi,[11] who discussed the irradiation facilities, radiochemical techniques, counting techniques, and computer data handling. The irradiation system is composed of six irradiation channels, a fast pneumatic system, and a 30-position storage and transfer rack. The advantages of the system in oceanographic applications were stressed. The radiochemical techniques include the use of "inorganic ion separators" (IIS),

which have potential for simple and fast radiochemistry, especially elimination of sodium. The counting system consists of two complete gamma spectrometers with various detectors, including a Ge(Li) semiconductor, two pneumatic sample changers, and different readout units. Useful computer programs were outlined briefly.

Computer programs were described by Pagden[12] which use published nuclear data and spectrometric criterions in calculations that enable a user to know what radioisotopes may possibly be present in a sample. The programs are based on the observation of gamma-ray spectrums of various activation products; the spectrums are detected with Ge(Li) detectors.

(HPR)

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10. R. Chesselet, Application of Neutron Activation Analysis to the Study of the Composition of Marine Aerosols, Center for Low-Level Radioactivities, National Center for Scientific Research, Gif-sur-Yvette, France.
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12. I. M. H. Pagden, Some Programs for the Resolution of Gamma Ray Spectra into Their Components, Bedford Institute of Oceanography, Canada.

The Use of Ionization in the Air for Lightning Protection

By G. Berio*

Supplementary Keywords: *ionization of gas; americium-241.*

Abstract: *The E. F. (électricité froide) lightning rod, which uses eight ^{241}Am sources to promote the ionization of air is described. This rod has an effective radius of 250 m and is being used extensively in Europe to protect commercial installations from lightning.*

The two classical methods for protecting buildings and other structures from being harmed by lightning are the Franklin lightning rod and the Faraday cage. The Faraday cage, however, is not practical for modern buildings. The Franklin lightning rod, developed by Benjamin Franklin in the eighteenth century, is based on the principle that a grounded point high in the air will cause ionization of the air and thus provide a track through which the lightning will discharge.

A Liechtenstein firm, General Protection Establishment, has recently improved the Franklin lightning rod, using a theory developed by Szilard[1] that air ionized by radiation would provide better protection than a standard Franklin rod. This rod is marketed under the name E. F. lightning rod. The letters E. F.

*General Protection Establishment, Hauptstrasse 539, FL-9490 Vaduz, Liechtenstein.

stand for "électricité froide," which means cold, or low-energy, high-voltage electricity.*

DESCRIPTION OF THE E. F. ROD

Figure 1 is a photograph and Fig. 2 a sketch[2] of the E. F. rod. The basic parts of the device are a stainless-steel cylindrical rod having a sharp point at the top and several ridges running longitudinally down the rod, an annular electrode having sharp edges directed toward the rod, an insulator that separates the rod and the electrode, and several ^{241}Am sources† in the electrode.

When the device is in operation, the rod is grounded and the electrode assumes the potential of the atmosphere. Under thunderstorm conditions the potential gradient between the rod and the electrode reaches high enough values that there will be electrical discharges between the sharp edges of the electrode and the ridges of the rod. This discharge is, of course, aided by the ionization of the air caused by the alpha particles emitted by the radioactive sources. The electrical discharge causes additional ionization of the gases, the net effect being to create an ionized cloud around the unit that will provide a path for the lightning to the rod where it will be grounded. At the present time, eight ^{241}Am sources are provided on each electrode. This ensures protection to the area within a radius of 250 m.

*A recent Euratom report[3] lists eight European firms that make radioactive lightning rods and states that there are between 5 and 10 thousand such rods installed in Europe.

Fig. 1 Photograph of E.F. lightning rod.

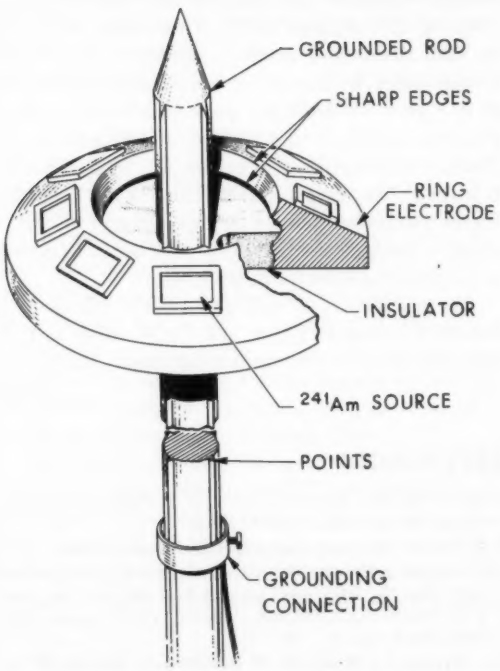

Fig. 2 Schematic diagram of E.F. lightning rod.

TESTS AND USE OF THE SYSTEM

The ionizing effect of an excellent Franklin installation was compared with that of an E. F. installation during periods of stormy weather in 1964. The measurements were taken on the Concord building (64 m) in Toulon, France. Under all trial conditions the E. F. installation, grounded on the same ground

†C. G. Invernizzi, President, United States Radium Corporation (Europe), 36 Avenue Krieg, Geneva, a long-term proponent of radioactive lightning rods, has been largely responsible for studies of lightning protection by ionization of air and for the development of the special ^{241}Am sources for lightning protection.

plate as the Franklin unit, at the same gradient values, gave an approximate rate of ionization 10^4 times that of the Franklin unit.

In such regions as Italy and the Spanish Peninsula—examples of European countries most affected by lightning—entire units of telecommunication systems, networks of electricity production and distribution, and fuel and gas systems, as well as a large number of important industries, such as Fiat, have adopted the E. F. system for lightning protection.

Fig. 3 E.F. protection installed (see the arrow) on the Acropolis, Athens, Greece.

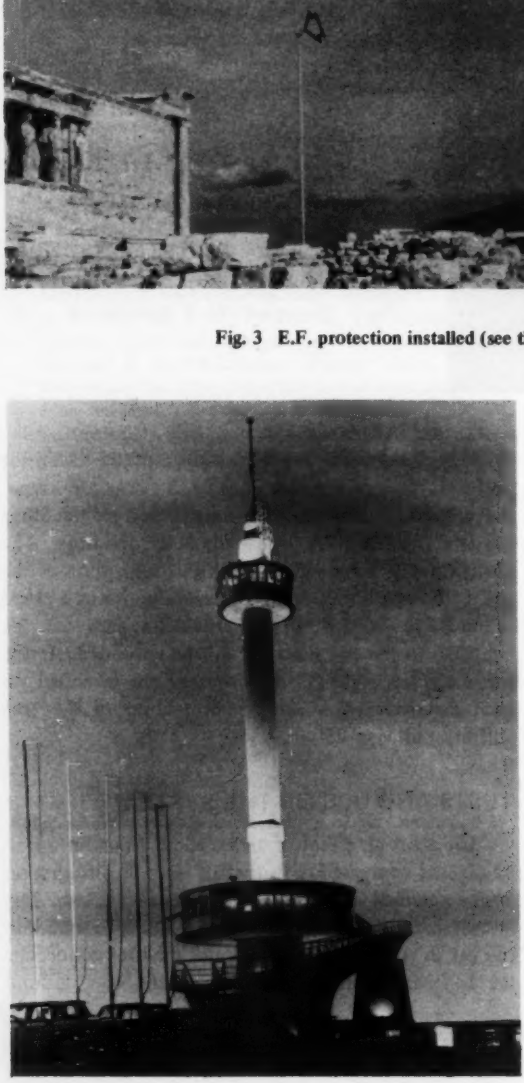

Fig. 4 An E.F. lightning rod on monument at Santander, Spain.

In the nuclear field the Pierrelatte Plant for isotopic separation in France has been protected since 1963 by 25 E. F. installations. This plant is situated in an area particularly prone to lightning. The French Commissariat a l'Energie Atomique has adopted the E. F. system to assure the protection of its plants at Fontenay-aux-Roses and Chinon. The French Electric Power Authority has also chosen this type of protection for its nuclear plant at St. Laurent des Eaux. The Italian government assures the protection of its nuclear plants of Saluggia and Garigliano with the E. F. system, as Euratom has done for its Ispra plant.

An installation of one unit on the Acropolis in Athens is shown in Fig. 3, and Fig. 4 shows an E. F. lightning rod on a monument in Santander, Spain.

(RHL)

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Water Permeability of Coating Films Using a Radioisotope Tracer Technique*

Supplementary Keywords: *measurement, other; physical property; coating; hydrogen-3.*

Abstract: *A radioisotopic tracer technique was developed for determining the moisture permeability of protective coatings. In tests with epoxy and alkyd resins, the method was more sensitive and rapid and results were more precise than by the ASTM method for measuring film penetrability to moisture.*

Corrosion of metal costs U. S. military and civilian establishments more than 10^{10} annually. Metal corrosion is electrochemical in nature, and water must be present for corrosion to occur. Painting is the method most widely used for isolating metallic surfaces from water or water vapor to prevent or decrease corrosion. However, because water or other corrosive materials may penetrate paint and reach the substrate, a study of the mechanism of water-vapor permeation through paint films should help in understanding the limitations of such films, aid in improving them, and thus contribute to corrosion control.

Unfortunately studies on the permeability of paints and other coatings to moisture have not given satisfactory data, largely because of the difficulty of measuring the amount of water vapor diffusing through a film. The quantity is usually too minute to be measured accurately by chemical means, and the diffused vapor is not in a form that is readily determinable by ordinary analytical methods. For example, the American Society for Testing and Materials (ASTM) standard method D1653-62T involves determination of the weight lost when a quantity of water passes through a sample film under a certain set of conditions, but the effect on diffusion of variations in temperature and pressure, for example, are not accounted for. At least a week is required for a readily measurable quantity of water to pass through a membrane, and even then accuracy is low.

Accordingly, a study was undertaken by the Naval Civil Engineering Laboratory (NCEL) to develop a new and improved method for measuring water-vapor diffusion through paint films, using tritiated water as a tracer. In the NCEL tests the effects on diffusion rate of various parameters—film thickness, vapor pressure and temperature, film composition, film-pigment type and concentration, and form of moisture (liquid or vapor)—were investigated. Detailed data from these tests are given in the original report, but only the methodology used is reviewed here.

*Extracts from Technical Report R-674, April 1970, by Eddy S. Matsui, Naval Civil Engineering Laboratory, Port Hueneme, Calif. 93041.

THEORY

The passage of water vapor through an organic membrane, such as a resin-based paint, is not a simple diffusion process but occurs in three stages:

1. Condensation of the vapor on and solution into one side of the film.
2. Diffusion through the film.
3. Evaporation from the other side.

The permeability, P_r [(g)(cm)/(cm^2)(hr)(cm Hg)], is thus the product of the vapor diffusion coefficient, D (cm^2/hr), through the membrane and the vapor solubility, S [g/(cm^3)(cm Hg)], in the membrane:

$$P_r = DS \tag{1}$$

The driving force for water-vapor diffusion through a membrane is the vapor-pressure difference between its two faces; and the amount of water vapor, Q, diffusing through a given membrane at a given temperature depends on the effective area, A, and thickness, d, of the membrane, the vapor-pressure differential, Δp, between the faces of the membrane, and the time, t, during which the diffusion occurs. The one-dimensional steady-state equation[1] is, from Fick's law,

$$Q = \frac{P_r}{d} A t \, \Delta p \tag{2}$$

The permeability, which characterizes the water-vapor-transmission resistance of the membrane under consideration, depends on the nature of both membrane and the permeating vapor. Incidentally, this equation is completely analogous to the basic heat-conduction equation,

$$Q = \frac{K}{d} A t \, \Delta T$$

where K is the conductivity and ΔT the temperature differential.

METHOD

Apparatus

A diffusion cell (Fig. 1), designed at NCEL, was constructed of Plexiglas and Pyrex tubing. Each half of the cell consisted of an exposure chamber and a water mantle, which maintained the desired temperature in the chamber and in the sample membrane during experiments. The membrane was placed between two fine-copper-gauze supports, which protected it from any damage due to a sudden change in pressure between the two chambers. The two halves of the cell were sealed by an O ring and a rubber gasket. A thermocouple probe on the lower chamber allowed direct monitoring of the membrane temperature. When the cell was assembled, the exposed membrane area was 20 cm^2.

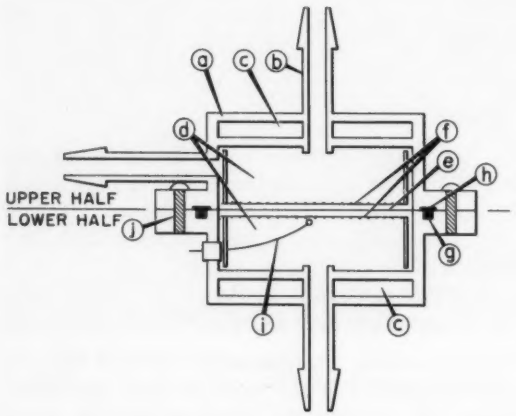
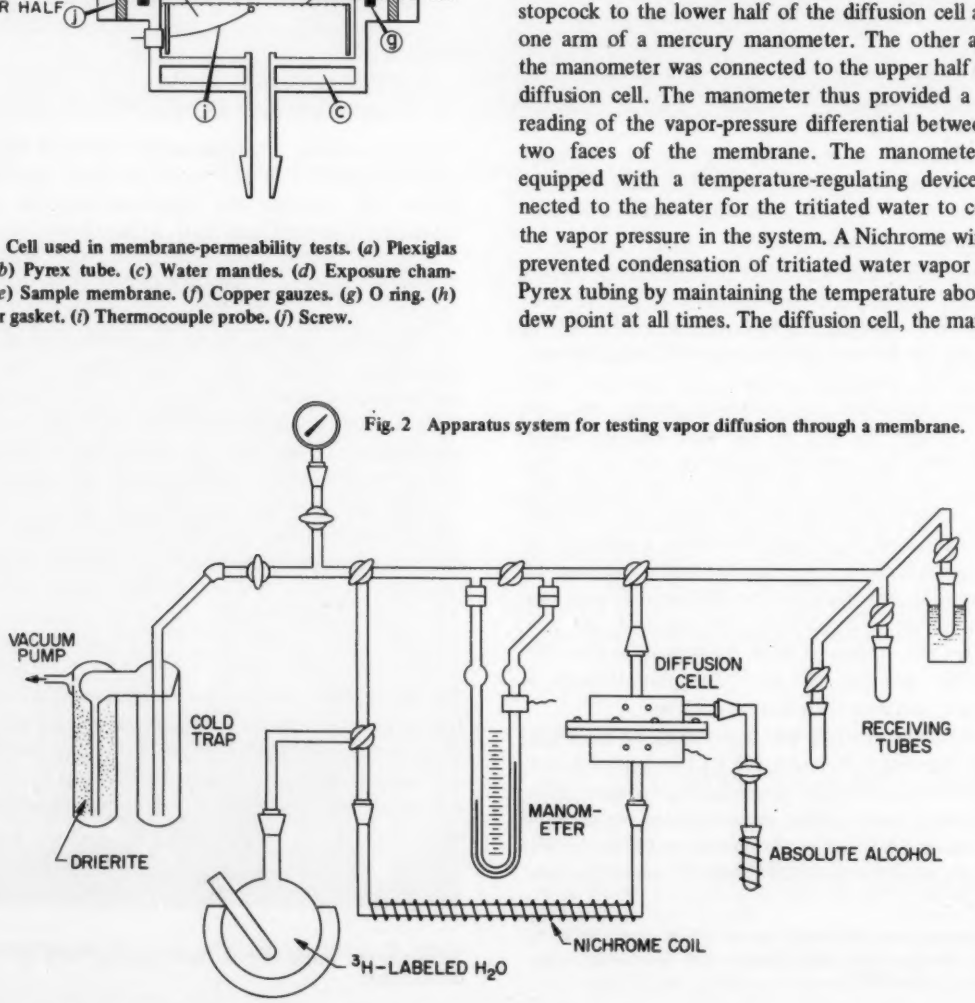


Fig. 1 Cell used in membrane-permeability tests. (*a*) Plexiglas wall. (*b*) Pyrex tube. (*c*) Water mantles. (*d*) Exposure chambers. (*e*) Sample membrane. (*f*) Copper gauzes. (*g*) O ring. (*h*) Rubber gasket. (*i*) Thermocouple probe. (*j*) Screw.

A vacuum system (Fig. 2) was provided to maintain a known, constant water-vapor pressure on the membrane surface so that Eq. 2 would be valid.

The system was fabricated from high-vacuum-grade Pyrex. A vessel containing tritiated water (approximately 15 mCi/ml) was connected through a T-shaped stopcock to the lower half of the diffusion cell and to one arm of a mercury manometer. The other arm of the manometer was connected to the upper half of the diffusion cell. The manometer thus provided a direct reading of the vapor-pressure differential between the two faces of the membrane. The manometer was equipped with a temperature-regulating device connected to the heater for the tritiated water to control the vapor pressure in the system. A Nichrome wire coil prevented condensation of tritiated water vapor in the Pyrex tubing by maintaining the temperature above the dew point at all times. The diffusion cell, the manome-

Fig. 2 Apparatus system for testing vapor diffusion through a membrane.



ter, or other element could be disconnected from the assembly by the use of stopcocks. The entire system was evacuated before the experiment.

Procedure

The membrane studied was placed between the two halves of the diffusion cell.

Tritiated water vapor was admitted to the manometer through the T-shaped stopcock. When the desired pressure had been reached, as indicated by the manometer, the vapor stream was switched to the lower half of the diffusion cell. This time was taken as the starting time of the experiment, i.e., $t = 0$. The stopcock in a line leading to a receiving tube, which was immersed in coolant, was then opened to condense and freeze out any tritiated water vapor that passed through the membrane. Freezing of the receiving tube ensured a constant pressure differential between the two faces of the membrane since any vapor that passed through the membrane would be condensed and frozen.

After a predetermined length of time—between 1 and 2 hr—the tritiated-water vessel was isolated from the rest of the system by turning the T-shaped stopcock, and this time was recorded as the end of the experiment. A vessel of absolute alcohol was warmed to release alcohol vapor into the upper half of the diffusion cell and purge it of any residual tritiated water vapor, the vapor being carried to and condensed in the receiving tube.

The receiving tube containing the frozen-out tritiated water was removed from the vacuum system, and the activity was counted, using a liquid scintillation spectrometer. The amount of vapor that diffused through the membrane was used to calculate the diffusion rate, R, in mg/(cm^2)(hr) and the permeability constant for the membrane in (mg)(mm)/(cm^2)(hr):

$$R = \frac{N100}{aAtk}$$

$$P_r = \frac{Nd100}{akAt\Delta p}$$

where N is the activity in counts per minute, a the specific activity of the tritiated water in counts per minute per milligram, and k the efficiency of the scintillation counter in percent; the other symbols have the same meanings as in the earlier equations, with A in square centimeters, d in millimeters, t in hours, and p in centimeters of mercury.

To decrease the random error of counting to less than 1% at the 95% probability level, each sample was counted to register 40×10^4 or more counts per measurement. A minimum of five condensates was collected for analysis after a steady rate of diffusion had been attained. The counting efficiency of the liquid-scintillation counter was determined by applying the channel-ratio method described by Buch.[1]

The results were processed by computer techniques. The spectrometer was loaded with up to 100 samples, and each sample was counted. The number of counts from each channel was automatically put on punch cards, which were fed into the computer along with other essential data. The computer printed out in tabular form the counting rate, channel ratio, counting efficiency, diffusion rate, and the permeability constant of each sample.

COMPARISON OF RADIOTRACER AND ASTM METHODS

The water-vapor-diffusion rate obtained by the radiotracer method was compared with that obtained with the same films using ASTM method D1653-62T. The ASTM method uses a two-part permeability device—a shallow flanged cup and a flat ring matching the flange on the cup. Water is poured into the cup, and the film under test is held tightly between the cup and the ring by clamps.

The assembled cup was placed in a desiccator over P_2O_5 and weighed every 24 hr for 1 week. The desiccator was in a well-ventilated room where the temperature was maintained between 70 and 85°F. The rate of water-vapor passage through the film was determined from the weight-loss rate.

Since the amount of moisture passing through a film is affected by the film thickness and since it is very difficult if not impossible to produce films of exactly the same thickness, the films used in the ASTM test were first used in the radiotracer experiments.

The coefficient of variation (a measure of the relative dispersion about the sample mean) values determined by the ASTM method were considerably larger than those determined by the radiotracer method (Table 1).

The greater precision of the radiotracer method was shown by the results of the F test—a statistical measure used to compare the precision of two sets of measurements by taking the ratio of two variances, i.e., the variance obtained in the radiotracer method divided by that obtained in the ASTM method. When the ratio of the variances exceeds the critical value of F, which is obtained from a statistical table, there is a

Table 1 Comparison of Water-Vapor-Diffusion Rate Through Alkyd Film as Determined by the Radiotracer and ASTM Methods

Alkyd film thickness,* mils	Diffusion rate,† $\mu g/(cm^2)(hr)$		Standard deviation		Coefficient of variation, %	
	Radiotracer method	ASTM method	Radiotracer method	ASTM method	Radiotracer method	ASTM method
0.9	358.30 ±17.94	380.38 ±41.91	14.43	33.71	4.02	8.86
1.9	197.33 ±6.55	196.32 ±20.35	5.27	16.37	2.67	8.32
2.7	151.69 ±14.15	136.80 ±14.57	11.38	11.72	7.50	8.56
3.5	102.58 ±4.83	132.48 ±98.26	3.89	79.03	3.79	59.66‡

*Unpigmented alkyd film (TT-R-266, type II).
†At 95% confidence level.
‡Had not attained a steady state of flow after 3 days.

significant difference in precision between the two systems.

In the NCEL experiments the critical F values at the 95 and 99.9% levels were 3.37 and 5.30, respectively. The F ratio obtained, 19.78, greatly exceeded these two critical values. This indicated that the NCEL radiotracer method was considerably more precise than the ASTM.

The sensitivity of the measuring system used in the radiotracer method can be increased to measure as low as 1 μg or less, where the analytical balance used in the ASTM method is accurate to only ±100 μg.

Results are obtained more rapidly by the radiotracer method. Once a steady state of flow has been attained, the diffusion rate can be measured in 1 to 2 hr, compared with a week for the ASTM method.

The radiotracer method permits separate control of various parameters, while the ASTM method does not. With the radiotracer apparatus, precisely monitorable vapor-pressure differential and temperature provide the means for examining separately the effects of vapor pressure and temperature on film permeability. With the ASTM method, temperature cannot be monitored without affecting the vapor pressure.

Further details of the sample preparation, the computer program, and the reliability of the counting system are given in Ref. 2. (MG)

Editor's Note: A related article appeared in *Isotopes and Radiation Technology*, 8(1): 60-64 (Fall 1970), A Radiochemical Study of the Diffusion of Ions Through Protective Films by A. L. Glass and J. Smith.

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Alpha-Particle Densitometer for Measuring the Density of the Martian Atmosphere

Summarized by Martha Gerrard

Supplementary Keywords: *source, alpha; measurement, density; measurement and control system; space; americium-241; polonium-210; curium-242; X-ray fluorescence.*

Abstract: *A feasibility study* indicated that an alpha-particle densitometer may be used to measure the density of the Martian atmosphere, and construction of a prototype instrument is recommended.*

It is expected that, within the next decade, instruments will be landed on Mars which will send back vertical atmospheric density profiles during the entry descent and then diurnal and seasonal surface atmospheric density variations during the rest of the instrument's life. Direct measurement of density by determining the amount of interaction of the atmosphere with radiation from radioisotopes offers great promise. The interaction of matter with such radiation depends only on the amount of matter involved and not on its pressure and temperature, except as these parameters affect the amount present. However, if pressure, temperature, and average molecular weight are known, internal checks can be made.

During the period July 1968–May 1969, a theoretical study was made of an alpha-particle densitometer, and properties of system components were determined. In the system considered (Fig. 1), an alpha-particle source would be separated from a detector by a fixed distance, D, and the particles would pass through the atmosphere under study to reach the detector. Those reaching the detector would generate a signal, which would be analyzed to give the density of the gas involved. Prior to use, the analyzer output would be measured for several known gas densities to give calibration curves. Thereafter the density of a gas of the same composition could be measured.

Two variants of the system are (1) the thin-source system, which uses a monoenergetic alpha source and measures the average energy loss; and (2) the thick-source system, which uses a broad-spectrum source and measures the count rate above a fixed threshold. For either system, with a gas mixture of CO_2, N_2, and Ar—the components thought to be significant in the Martian atmosphere—the density, ρ, is given by

$$\rho_{gas} = \rho_{CO_2} + \rho_{N_2} + 0.67\rho_{Ar}$$

The thin-source system gives greater accuracy at high densities, high alpha source energies, and large source–detector separations. The thick-source system can be made to give a nearly constant fractional density error with accuracy at low densities of about 0.5×10^{-6} g/ml. Since composition errors of a few percent are likely to be present, the thick-source system is preferable to the thin. Maximum ground-level density of the Martian atmosphere is estimated at about 40×10^{-6} g/cm^3, and systems will be designed for densities up to 80×10^{-6} g/cm^3, i.e., with a safety factor of 2, to allow for possible landing in a depression or for actual densities somewhat greater than estimated.

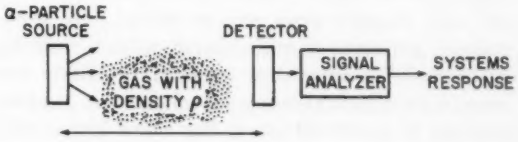

Fig. 1 Basic design of alpha-particle densitometer for determining gas density.

One requirement for the system is that it be able to stand complete decontamination prior to launching to avoid contamination of Mars with Earth organisms. Further, a Martian lander will be in flight from Earth to Mars for about 6 months, and, if there is no shield en route between the detector and source, the detector will be continuously irradiated during this time. Since at least several months on the Martian surface will be necessary, the detector should have a lifetime of more than a year, or 3×10^7 sec.

Alpha particles lose energy nearly continuously rather than being completely absorbed, like X rays. The chief difficulty with a particle system is that the response is somewhat dependent on composition, but,

*Frederick A. Hanser and Bach Sellers, Feasibility Study of Alpha-Particle Densitometers for Measuring Planetary Atmosphere Density, Report NASA-CR-66825, June 1969 (154 pp).

for the expected composition of the Martian atmosphere, this may not be too critical. The system can be designed so that CO_2 and N_2 produce nearly the same response, and argon can be measured by other methods and its effect compensated for. The argon component can be obtained by measuring the attenuation of the 3.3-keV neptunium M X rays from a ^{241}Am source, which would double the preliminary estimates of 0.75 lb and 200 to 500 mW power. Use with an X-ray-attenuation system would allow the values of $\rho_{CO_2} + \rho_{N_2}$ and ρ_{Ar} to be determined separately. When no composition information is available, the alpha-particle system alone will measure the density of the Martian atmosphere to ±8%. If the composition is known, the error may be decreased to ±2%.

Alpha sources considered were ^{241}Am, ^{210}Po, and ^{242}Cm for thin sources and only the first two for thick sources.

EVALUATION OF A HIGH-SPECIFIC-ACTIVITY ^{60}Co GAMMA SOURCE USED IN A MONOCHROMATOR

Under contract to the USAEC Division of Isotopes Development, Texas A & M Research Foundation has installed a 40-thousand-Ci ^{60}Co source and used it in various studies on resonance fluorescence Compton scattering. Several M.S. theses have been written and papers presented at the American Physical Society using the data obtained. USAEC Report ORO-662, by John A. McIntyre, May 25, 1969, reviews the program briefly. (MG)

Section III

Isotopes and Radiation Technology

Food Irradiation

Potato-Sprout Inhibition by Radiation. Part 1

By F. E. McKinney

Supplementary Keywords: *food preservation; potato and onion; review, technical; bibliography; industry, food; industry*

Abstract. *The use of radiation to inhibit sprouting of potatoes is reviewed. Early research in the field and the legislation it led to are covered. The results of 16 years' research in 23 countries, including the United States, are presented. Also included is a comparison with chemical sprout inhibitors and the currently accepted explanation of how radiation accomplishes this beneficial task.*

On July 8, 1964, the United States became the third country to officially approve the use of ionizing radiation to inhibit sprouting of potatoes. According to the International Atomic Energy Agency,[1] the first country to clear this treatment was the USSR on Mar. 14, 1958; Canada approved on Nov. 9, 1960. Since the U. S. action, Israel (July 5, 1967) and Spain[2] have given full approval. France, West Germany, and the Netherlands all have temporary marketing approvals.[3]

The popular press has covered the subject well, and the technical literature on radiation inhibition of sprouting is extensive. Radiation does inhibit sprouting (Fig. 1). However, 5 years after the first Food and Drug Administration (FDA) approval, the process has not been commercialized in the United States. There have been some military procurements for test purposes,[4] but the housewife cannot buy irradiated potatoes at the supermarket. Interest in irradiation of potatoes remains high; 26 countries have research programs[5] on this application of radiation. Hence it may now be appropriate to review the literature on radiation inhibition of sprouting in potatoes. Three noteworthy reviews[6–8] exist, but no one of them has attempted any real measure of completeness. Freund[7] explains why: "An attempt to correlate all potato irradiation research and put it on a common basis is handicapped by the subjective nature of many of the findings and by the almost total absence of a common basis for reporting." His point is well-taken, and, thus, in this review, comparison and evaluation will necessarily be subordinate to reporting.

This is the first article in a planned three-part series for *Isotopes and Radiation Technology*. This part will provide introductory material, report on legislation, cover the history of the early research into the problem, treat in detail results on sprouting, compare the effects of radiation with those of chemical inhibitors, and describe the sprout-inhibition mechanism. The second article will discuss the effects of radiation on the chemical components, cooking properties, and microbial resistance of the potato. The third article will describe economics, irradiator designs, growth improvement of seed potatoes, feeding studies, and shipping studies. The combined series is intended for later publication as a single report.

POTATO HISTORY AND PRODUCTION

History

The so-called common Irish potato was first found being cultivated by natives in the South American highlands. In the second half of the 16th century, Spanish explorers introduced the potato into Europe. From Europe the potato was spread throughout the English-speaking colonies of the world. Most stories of the introduction of the potato into England from Virginia or into Virginia from Spain are legend.[9]

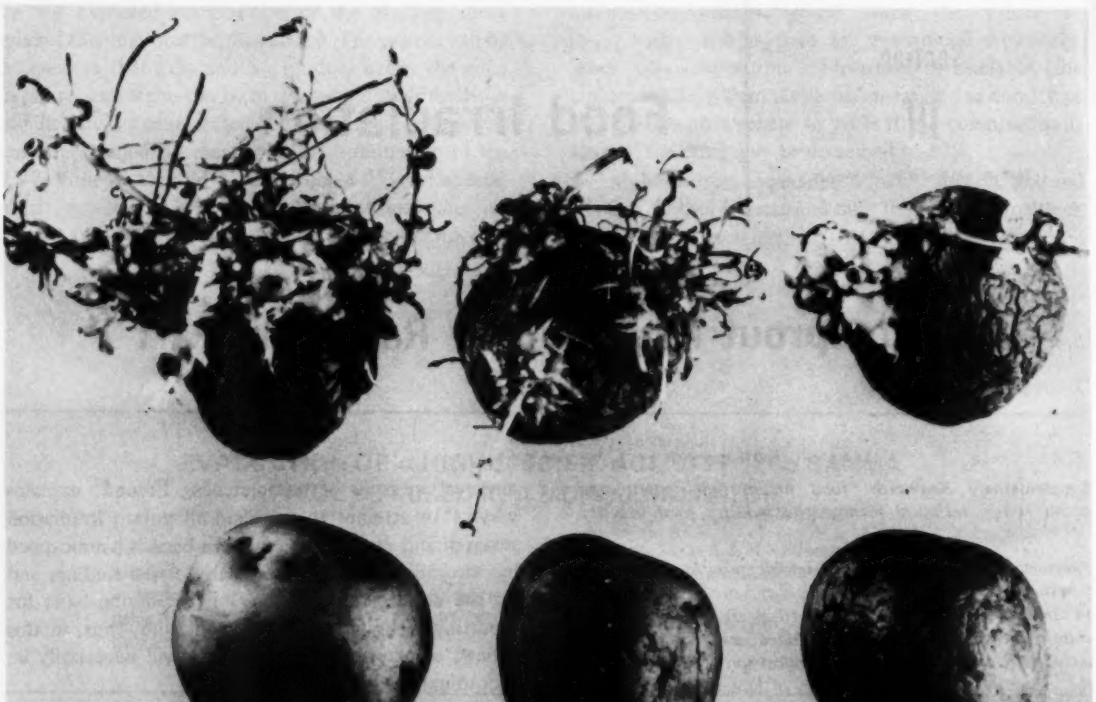

Fig. 1 Typical result of radiation sprout inhibition. Doses ranged from 0 (upper left) to 106 kR (lower right).

Production

Peak acreage and peak per capita consumption in the United States occurred in 1910. More than 3.6×10^6 acres were planted in potatoes, and per capita consumption was 200 lb/year. Today, production is nearly three orders of magnitude greater than in 1910, but potato acreage has declined to about one-third the 1910 figure. Per capita consumption is ~135 lb now; about one-third of this is as commercially processed potatoes of some form.

Potatoes are grown in every state and in one place or another throughout the whole year, but 72% of the crop is grown in 26 states and is harvested in October through December. Table 1 shows the distribution of growers and harvesting dates. The Russet Burbank variety is grown most often and accounts for ~35% of the crop. It is a superior baking potato, and processors think it preferable for frozen and dehydrated products. The Kennebec variety is considered best for potato chips. Other important varieties* grown in the United States are Katahdin, Red Pontiac, Irish Cobbler, and Sebago.

POTATO STORAGE

According to Bulletin 500 of the Idaho Agricultural Experiment Station,† Aberdeen, the ideal potato storage environment consists in a constant temperature of 45°F (7.2°C), a relative humidity of 95%, and an air flow of 10 ft^3/min per ton of potatoes. These conditions stimulate healing of bruises and other

*There are almost as many varieties of potatoes as there are varieties of roses; this list includes those varieties most often grown commercially. The index to the entire series of three articles will include all varieties encountered in preparing this review. (FEM)

†The help of W. C. Sparks in providing the background material for this section is gratefully acknowledged.

Table 1 Seasonal and Regional U. S. Potato Production—1962 (Ref. 7)

Crop	Harvest	Major producing states	Percent of yearly crop	Varieties
Winter	January to March	Fla., Calif.	1.6	White Rose, Red Pontiac, Red Lasoda, Norland
Spring				
Early	April to May 15	Fla., Tex.	1.3	Sebago, Red Pontiac, Red Lasoda
Late	May 16 to June 30	Calif., Ariz., N. C., Ala.	8.1	Cobbler, Kennebec, Sebago, Red Pontiac, Red Lasoda, Norland, White Rose
Summer				
Early	July 1 to August 15	Tex., Del., Va., Calif.	4.8	Sebago, Katahdin, Kennebec, White Rose, Cobbler, Red Pontiac, Red Lasoda, Norland
Late	August 16 to September 30	N. J., N. Y., (L. I. only), Wash., Oreg., Wis., Idaho, Colo., Calif.	12.6	Early Gem, Russet Burbank, Red Pontiac, Red Lasoda, Norland, Red McClure, White Rose, Katahdin, Kennebec, Cobbler
Fall	October to December	Maine, Idaho, Minn., N. Dak., N. Y. (including L. I.), Colo.	71.6	Katahdin, Russet Burbank, Red Pontiac, Kennebec, Sebago, Red Lasoda, Norland, Red McClure, Cobbler

wounds; maintain the appearance and the food value of the tuber; keep rot development, shrinkage, and pressure flattening at a minimum; retard sprout growth; and prevent greening. Under these conditions, tubers treated with a chemical sprout inhibitor can be maintained sprout free and in a high state of quality for 10 to 12 months. The ventilation cools tubers by removing field heat; it also provides oxygen for healing wounds, helps maintain a constant temperature, minimizes storage losses from rots, and reduces sprouting.

These ideal conditions are only approximated in practice. *Common* storage is in large warehouses cooled by outside air ranging from 4°C in winter to 20°C in midsummer; humidity is not controlled. At the other extreme of the scale, some processors provide storage facilities in which refrigeration systems and humidifiers feed blower systems which circulate the air through the piles of potatoes and maintain near-ideal conditions. Every variation possible between these extremes can be found: some growers use fans to pull in outside air, some just leave the warehouse door open. Instead of humidifiers, some growers place wet burlap sacks in the airstream.

At a low relative humidity, potatoes lose moisture to the air and become soft and flabby. At very low temperatures, freezing damage occurs and a permanent sweet taste develops; some change in color can also be expected. At too high a temperature, early sprouting is encouraged, and if a high relative humidity occurs with the high temperature, microbial growth and rot can increase.

Under common storage conditions, potatoes harvested in the fall start sprouting when the weather warms up in the spring. Potato chip manufacturers usually hold their stock at relatively high temperatures to prevent sugar formation; this practice leads to early spoilage, and chippers consequently have to purchase early potatoes from the next crop at higher prices and transport them to the manufacturing plant. Unlike other potato processors, who locate their plants close to the source of supply, manufacturers of potato chips and other potato snack foods usually locate their plants close to shipping and distribution facilities which will enable them to keep a fresh product on the market and to reduce damage due to the excessively friable nature of the product.

LOSSES DUE TO SPROUTING

Estimates vary widely on the extent of sprouting and whether or not additional controls are actually necessary, although most observers agree that sprouting losses should be minimized further if possible. Table stock is no good once it begins to sprout; indeed, sprouts contain the toxic alkaloid solanine. One report[10] states that most of the sprouting occurs in consumers' homes and cannot be assessed accurately. Another report[11] states that in 1965 at least 5% of U. S. potato production was lost because of sprouting,

and Powers[12] uses this figure to estimate that annual losses due to sprouting probably amount to between $\$75 \times 10^6$ and $\$100 \times 10^6$. On the other hand, Bradley[13] notes that over 80% of the Pacific Northwest crop goes to processors, and consequently there is little need there for sprout control. He argues that disease and rot cause more damage than sprouting and suggests that doses sufficiently high to kill microorganisms be used on potatoes. Freund[7] points out that the extent of the sprouting problem depends on the growing area, storage requirements, and end use of the potatoes. Freund[7] and Smith[14] both estimate that sprouting inhibitors, whether radiation or chemical, could be used to treat 40×10^6 to 50×10^6 lb of potatoes annually. At present, only a small portion of shippers and processors are using sprout inhibitors; that portion is growing rapidly, however.

LEGISLATION

In the United States, unlimited consumption of irradiated food requires the approval of the Food and Drug Administration (FDA) because radiation used for this purpose is defined by government regulations as a food additive. Clearances must therefore be obtained from FDA to market irradiated food. The use of radiation to inhibit sprouting of potatoes[15] was approved by the FDA on July 8, 1964. (The order was dated June 30, and this date is sometimes cited[10] as the approval date, but the order specifically states that it is effective as of the date of its publication in the *Federal Register*—i.e., July 8.) The order approved the use of gamma rays from ^{60}Co to provide doses of 5 to 10 krads to potatoes. On Oct. 10, 1964, use of ^{137}Cs to provide the same dose was approved.[16] The maximum dose was later increased to 15 krads to accommodate designs of commercial irradiators.[17] (To process potatoes in economically feasible quantities would require the use of large pallet boxes. Because gamma radiation would be attenuated passing through the outer potatoes, a dose uniformity ratio of about 2 was necessary to obtain the minimum effective dose of 8 krads in the center of the boxes. To achieve this, a maximum dose of 15 krads was required and was approved.)

EARLY RESEARCH

Although the Russians cite very early work[18] in the use of radiation to inhibit sprouting in potatoes, modern work is generally agreed to have begun with Sparrow and Christensen[19] in 1954. Most of the early work grew out of mutation and radiation-effect studies. In 1950 Sparrow and Christensen[20] reported that potatoes irradiated* to 4800 R from an X-ray machine produced only 4% as much crop as control potatoes, and Hagberg and Nybom[21] reported in 1954 that sprouts already growing on potatoes died after a 10- or 20-kR dose from an X-ray machine and did not reappear even when the potato was planted.

The research of Sparrow and Christensen[19] was based on work with the Katahdin variety irradiated at doses of 1.25, 5, 10, 20, 80, and 106 kR from a ^{60}Co source. Sprouting was reduced by the two lower doses and was completely inhibited by doses of 20 kR or more. Potatoes irradiated at 20 kR were still firm after 18 months of storage, and a taste panel found no undesirable tastes in any of the irradiated samples.

Shortly thereafter, Hannan,[23,24] Brownell and Nehemias,[25] and Mikaelsen and coworkers[26] all reported similar results. Hannan gave one-half a potato a 25-kRep dose from 2-MeV cathode rays and compared that half with the untreated half; sprouting was inhibited, but some radiation damage occurred. Brownell's results[25] closely paralleled those of Sparrow and Christensen; a 20-kRep dose inhibited sprouting. The Norwegian researchers[26] found no sprouting of potatoes which had been stored 8 months after receiving doses from 5 to 20 kRep. Control potatoes had a 9% weight loss, as compared to a 4% loss in the irradiated potatoes.

THE 1955 BROOKHAVEN CONFERENCE

At Brookhaven National Laboratory (BNL) on May 25, 1955, the U. S. Atomic Energy Commission convened its researchers and contractors with members of the potato-growing and -processing industry for the first large-scale meeting on this new application of radiation; almost 140 people attended.[27] The conference proceedings were not published, but a verbatim transcript[28] was made. Smith[14] reviewed current problems and methods of storage. In the northern states, potatoes harvested in the fall keep until May or June because of low ambient temperatures. Smith acknowledged that temperatures of less than 45°F

*Throughout this review the dose units used by the researchers have been retained. Conversion to a consistent unit is not justified because of the limitations on dosimetry, statistics, and other factors involved in dose measurement. In any case, the differences are relatively minor. The reader, therefore, will encounter R, kR, kRep, and krad—whatever the researchers cited as dose units. (FEM)

(7.2°C) lead to excessive sugar levels. High sugar level is undesirable in potatoes to be processed, especially french fries and potato chips, because of the Maillard reaction which causes the product to be dark brown. Chemical sprout inhibitors have been used; these include the methyl ester of naphthalene acetic acid, tetrachloronitrobenzene, maleic hydrazide, and chloro-isopropyl phenylcarbamate. Application costs of chemical inhibitors range from 4 cents to 7 cents per bushel.

Sparrow and Schairer[29] essentially reiterated the earlier report.[19] Four different types of radiation were used: X rays from a machine, gamma rays from ^{60}Co, fast electrons from an accelerator, and fast neutrons from reactors. A 4800-R dose of X rays had about the same effect as 1200 Rep of fast neutrons—a type of radiation not likely to be used commercially. Fast electrons even at 20 kR did not produce good results, presumably because even a little dirt or a flap of tissue over the eye would shield the sprout mechanism from the effects of the bombardment. Gamma rays and X rays gave the best results, with an 8- to 10-kR dose being the most effective.

Sawyer, Dallyn, and Cotter[30] irradiated Green Mountain potatoes with the ^{60}Co source in the Brookhaven Gamma Garden; 10-kR or larger doses inhibited sprouting at any temperature. Potatoes stored at 50°F (10°C) were inhibited by a 7.5-kR dose. Katahdin-variety potatoes were also tested, 1 year later, with similar results. These researchers pointed out that sprouting was a severe problem with potatoes grown on Long Island, because the temperature at harvest is high enough to break dormancy and to initiate immediate sprouting.

Long Island potatoes are infested by the golden nematode, and Fassuliotis and Sparrow[31] attempted to control this pest with irradiation. The LD_{50} for the nematode was apparently 10 kR, which is the usual one for sprout inhibition. A solution to the nematode problem could result with the adoption of a radiation sprout-inhibition program.

(Effects of radiation on cooking quality, wholesomeness, and biochemistry of potatoes reported at the BNL conference will be reviewed in later articles. The papers comparing different sources of radiation and the presentations of various irradiator designs will also be covered later.)

During a discussion period, Nielsen[32] pointed out that one source of difference in response of different varieties of potatoes to radiation could easily be the variations in skin thicknesses of the varieties. Rogers[33] made the point that ionization in the cell structure causes the desired effect and that the potato does not differentiate between radiation sources. For commercial treatment of bulk quantities, penetrating radiation will obviously be necessary. If only the skin and eyes of the potato are treated, electron-beam irradiation may be satisfactory. Most accelerators produce a small, narrow beam which would have to be widened to treat quantities of potatoes. The usual method of widening the beam reduces the energy of the beam. Hatch and Regan[34] noted that the use of fission products, especially ^{137}Cs, might be stimulated by this possible application. Ballantine[35] posed a crucial question: would irradiation inhibition of sprouting cause the housewife to pay 2 cents more or 2 cents less per pound for potatoes? There were various replies from the attendees at this late discussion, but the general opinion was that the housewife would pay less.

RESULTS OF SPROUTING STUDIES

Radiation inhibition of potato sprouting has been studied in nearly all the major countries of the world. Although most of the literature covered in this article is from the United States, results from Canada and 22 other countries are presented. Because the reader would surely find the repetition of "such-and-such variety irradiated at *x* dose and *y* dose rate, stored at whatever temperature and relative humidity for so long a time" seemingly endless, the results of the experiments are presented in the text, but the experimental conditions are presented in a capsule form:

Variety: Dose: T, °C: R.H.: Δt: t: Ref.:

where *Variety* is the variety of potato used in the experiment; *Dose* is the dose specified by the experimenter (presented in the units—kRep, kR, or krad—he uses); *T* is the storage temperature in °C (converted from °F, if necessary); *R.H.* is relative humidity; Δt is the time between harvest and irradiation; *t* is the length of storage time; and *Ref.* is the reference where full details may be found. Not all these data are given in all cases, of course.

United States

After Sparrow and Christensen[19] and Brownell and coworkers[25] reported the results of their early studies,

Variety:	*Dose:*	*T, °C:*	*R.H.*	*t:*	*Ref.:*
Green Mountain	1.25 to 40 kR	4.4 to 21.1°	30 to 40%	6 months	36

many others investigated this use of radiation. Sawyer and Dallyn[36] established that a 10-kR dose inhibited sprouting at several relatively high storage temperatures (Table 2). In a study[37] of both gamma radiation and chemical sprout inhibitors, both ^{60}Co and an accelerator were used. A 10-kR dose completely inhibited sprouting. Lower temperatures gave longer storage times. Varietal differences were investigated in four experiments by Sawyer and Dallyn,[38] with the results shown in Table 3 and Fig. 2. An early review of Pedersen[39] covered 32 references. Heiligman[40] noted that, at high doses, some softening and shriveling occurred. A 5-kRep dose retarded but did not inhibit sprouting. The 10-kRep dose was sufficient to inhibit sprouting at 13°C, but some small sprouts did appear on the lot stored at 22°C. There were no sprouts on

Table 2 Sprouting on Irradiated Potatoes After 6 Months of Storage (Ref. 36)

Storage temperature, °F(°C)	Average sprout length, in.					
		Irradiation dose, kR				
	Control	1.25	5	10	20	40
40(4.4)	1/8	1/8	None	None	None	None
50(10)	12	6	1	None	None	None
70(21.1)	30	30	30	None	None	None

Variety:	*Dose:*	*T, °C:*	*t:*	*Ref.:*
Green Mountain Katahdin	2.5 to 12 kR	4.4, 10, 21.1°	10 months	37

Variety:	*Dose:*	*T, °C:*	*t:*	*Ref.:*
Green Mountain Katahdin Cobbler Kennebec Saco Russet Burbank	5 to 20 kR	10 and 21.1°	8 months	38

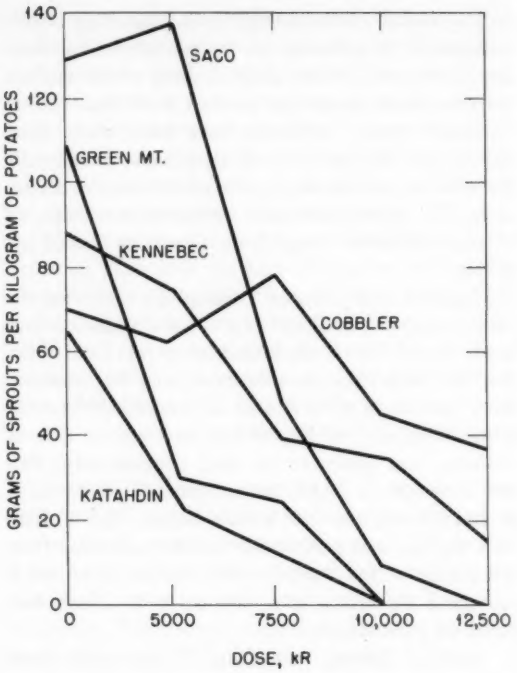

Fig. 2 Variety-dose relation for potatoes stored at 50°F (10°C) for 8 months.

Variety:	*Dose:*	*T, °C*	*R.H.:*	*Ref.:*
Sebago Russet Rural	5 to 200 kRep	13 and 22°	85 to 90%	40

Table 3 Loss of Potatoes After 8 Months of Storage (Ref. 38)

Irradiation dose, kR	Katahdin		Green Mountain		Kennebec		Russet Burbank	
	Sprouting*	Shrinkage†	Sprouting	Shrinkage	Sprouting	Shrinkage	Sprouting	Shrinkage
0	31.4	10.0	120.4	8.8	38.3	12.2	62.0	12.8
5	10.6	7.5	32.5	13.4	30.5	12.2	37.2	12.8
7.5	2.5	9.9	13.6	10.5	26.2	12.2	35.1	10.0
10	0.8	8.2	3.2	10.8	10.5	11.8	22.8	8.1
12.5	0.5	4.4	-	9.1	3.5	12.0	6.0	6.1
15	0.1	6.8	-	8.3	0.6	9.9	0.1	5.4

*Grams of sprouts per kilogram of potato.
†Percent of original weight.

any lot irradiated at doses of 15-kRep or greater. The weight loss from potatoes treated at doses larger than that needed for sprout inhibition was greater than that from controls; potatoes irradiated at doses at or near the minimum for sprout inhibition also showed higher weight losses than the control potatoes.

The group under Brownell at Michigan had made early studies[41] with Russet Burbank variety potatoes. Tests conducted after 5 months showed no sprouting

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*t:*	*Ref.:*
Russet Burbank	7 to 28 kRep	10°	50%	5 months	41

in the irradiated potatoes. A subsequent report[42] summarized the experiments. Again, 10 kRep seemed to be the best dose. After 5 months, lots that had received this dose were 86 to 98% useable. Those which received doses greater than 5 kRep did not

Variety:	*Dose:*	*T, °C*	*R.H.:*	*t:*	*Ref.:*
Russet Burbank Russet Rural Sebago Katahdin	5 to 200 kRep	1.7 to 26.7°	66 to 90%	5 months	42

sprout. Weight loss increased with increase in storage temperature; because of sprouting, controls lost more than did irradiated potatoes. Weight loss decreased with increase in relative humidity; again, controls lost more weight than did irradiated potatoes. In another experiment the weight loss of Sebago potatoes increased as the irradiation dose increased, a result which indicates that the sprout inhibition mechanism is simply one of mechanical damage rather than of cell destruction and reduced metabolism. When sprouts were irradiated, their growth ceased. When the potatoes were irradiated and the sprouts were shielded, sprout growth was not affected. The optimum conditions, reported by Brownell and associates,[43] are a dose of 10 kRep, T of 7.2°C, and 85 to 90% *R.H.*

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*t:*	*Ref.:*
Russet Burbank Russet Rural Sebago Katahdin	5 to 200 kRep	1.7 to 26.7°	60 to 90%	5 months	43

Ellis and coworkers[44] undertook to determine the optimum dose, curing schedule, time of irradiation, and storage temperature that are required to preserve four varieties for 18 months. The curing schedule was storage at 21°C and high *R.H.* for 7 days; potatoes

Variety:	*Dose:*	*T, °C:*	*Δt:*	*t:*	*Ref.:*
White Sebago Red Pontiac Katahdin Russet Burbank	5 to 15 kRep	5, 8.3, 12.8°	1, 2, or 3 months after harvest	2 years	44

were cured before irradiation, cured after irradiation, cured both before and after irradiation, or not cured. Dose and curing schedule were investigated at 5 and 12.8°C in one phase of the study, and optimum time to irradiate (with storage at 8.3°) in another. Ellis and associates intended to irradiate potatoes at three stages—immediately after harvest, at the midpoint of dormancy, and at the end of dormancy; however, the four varieties were obtained from four different locations in the United States at four relatively different harvest times. Therefore three arbitrary irradiation times were chosen: December 4, January 3, and January 30.

For White Sebago a 5-kRep dose prevented sprouting at 5°C, but a 7.5-kRep dose was necessary at 12.8°C. At the lower storage temperature, curing both before and after irradiation gave the best results, i.e., the lowest weight loss. At the higher temperature, curing before irradiation was sufficient. At 17 months the doubly cured potatoes stored at the lower temperature still appeared normal. There was little observable effect of the length of time before irradiating, although the potatoes irradiated January 30 had a slightly greater weight loss than the potatoes irradiated earlier.

The Red Pontiac variety required a 7.5-kRep dose at the lower temperature and a 12.5-kRep dose at the higher temperature to prevent sprouting. No curing effect was noted; no time-of-irradiation effect was observed. Appearance of the 7.5-kRep-treated potatoes after 17 months at 5°C was excellent; however, decay was excessive in potatoes stored at 12.8°C for 10 months.

The Katahdin variety, like the Sebago variety, required a 7.5-kRep dose to prevent sprouting when stored at 12.8°C, although a 5-kRep dose inhibited sprouting at 5°C. Time of irradiation after harvest did not affect the results; neither did curing.

A 5-kRep dose inhibited sprouting of Russet Burbank potatoes stored at 5°C and markedly reduced sprouting of those stored at 12.8°C. At the lower temperature, potatoes cured before irradiation had less weight loss than the other potatoes, but this effect was not noted at the higher storage temperature. This variety stores well, and the appearance of some

Table 4 Storage-Life Increase of Potatoes Caused by Radiation (Ref. 44)

Variety	Storage temperature, °F(°C)	Storage life from harvest, days		Extension, days	Extension, %
		Controls	Irradiated		
White Sebago	55(12.8)	90	325	235	261
	47(8.3)	170	385	215	126
	41(5)	330	415	85	26
Katahdin	55(12.8)	115	365	250	217
	47(8.3)	225	410	185	82
	41(5)	410	495	85	21
Red Pontiac	55(12.8)	130	325	195	150
	47(8.3)	175	450	275	157
	41(5)	300	625	325	108
Russet Burbank	55(12.8)	140	335	195	139
	47(8.3)	210	410	200	95
	41(5)	400	650	250	63

irradiated potatoes stored at 5°C was still excellent slightly over 2 years after harvest. Time of irradiation had some significance; potatoes irradiated January 4 after harvest on October 17 lost weight more slowly than did the other potatoes.

Ellis and associates[44] conclude that, for all the varieties except Red Pontiac, storage at 12.8°C results in the greatest increase in shelf life (Table 4). For all four varieties, a dose increase was required to inhibit sprouting at the higher storage temperature.

Emerson and coworkers[45-47] studied the effects of radiation on many fruits and vegetables. Under conditions designed to accelerate sprouting of potatoes, a 7.5-krad or greater dose was needed to inhibit sprouting. The controls showed a weight loss of 24.8% for Arenac and 23% for Ontario after 55 days; the 7.5-krad-treated potatoes lost 16.3 and 20.5%, respectively.

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*t:*	*Ref.:*
Arenac	5 and 7.5 krads	21.1°	35%	6 weeks	45
Ontario				55 days	46
Sebago					

A number of experiments were conducted on Idaho-grown Russet Burbank potatoes by Sparks and Iritani.[48] Potatoes were irradiated in 10-lb sacks lowered between spent fuel elements from reactors. In 5 years of experiments, no potato tested immediately after irradiation showed any induced radioactivity whatsoever. Table 5 gives results of early experiments,

Variety:	*Dose:*	*T, °C*	*Δt:*	*t:*	*Ref.:*
Russet Burbank	5 to 80 krads	Common, 3.3, 10, and 21°	2-week intervals up to 34 weeks	1 year	48

Table 5 Loss Data on Russet Burbank Potatoes 312 Days After Harvest After Being Kept in Common Storage* (Ref. 48)

Days after harvest	Percent loss						
		Irradiation, kRep					
	Controls	5	10	20	40	80	Mean
1	100	49	52	65	100	100	73
14	100	75	87	59	100	100	84
28	64	9	20	26	52	78	37
42	59	17	21	12	28	71	30
56	61	16	20	56	27	58	35
70	62	18	12	17	13	31	18
84	59	11	20	15	14	22	16
98	61	11	18	26	14	20	18
112	64	10	14	14	14	23	15
126	61	10	9	19	16	10	13
140	57	9	9	14	13	14	12
154	58	15	11	5	13	21	13
168	57	15	8	7	19	15	13
182	56	14	13	4	16	15	12
196	56	4	10	8	12	23	12
210	54	9	5	7	10	29	12
224	53	9	7	8	17	37	16
238	53	10	21	20	24	33	20
Mean	63	18	20	21	28	30	

*Cooled by ambient air only.

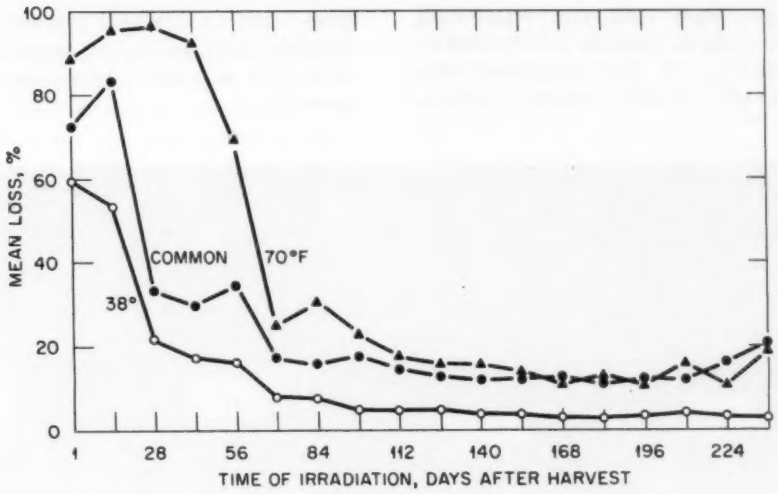

Fig. 3 Loss data on irradiated Russet Burbank potatoes under three storage conditions, 312 days after harvest. (From Ref. 48.)

and Fig. 3 summarizes the loss data at all doses and temperatures. Any potato with excessive sprouting, withering, or shriveling was discarded. Sparks and Iritani justify using the mean of the dose data in Fig. 3 by pointing out that time of irradiation had a much greater effect than did dose variation. At 3.3°C, controls lost less weight than did irradiated potatoes; but at higher temperatures, controls were the only potatoes that were completely discarded after 333 days of storage. In the 1958 to 1959 experiments, minimum dose was studied; no data were collected for more than 6 months. No treatment of less than 5 kRep prevented sprouting, and 10 kRep was concluded to be an optimum dose. Storage at 10°C gave better results than storage at higher temperatures. Results of the 1959 to 1960 experiments confirmed that a long delay after harvest before irradiation gives best shelf life. A constant storage temperature (10°C) gave better results than common storage. There was little dose effect among potatoes stored at low temperatures, but 5- or 10-kRep-treated potatoes stored better than other potatoes at intermediate storage temperatures, and potatoes given a 10-kRep dose kept best at 21°C.

The review of Freund[7] has already been mentioned. He concluded that a 7- to 10-krad dose should inhibit sprouting under any commercially practical storage conditions; his later addendum report[49] did not differ. Freund summarizes known varietal differences (Table 6). Although researchers have investigated storage periods of up to 2 years, Freund points out that anyone storing potatoes for more than 1 year is essentially competing with himself during the second year. His review also contains a summary of the commercially significant qualities of these six most important varieties.

Table 6 Sprout Inhibition Doses Required for Commercial Varieties of Potatoes

Variety	Dose, krads
Katahdin	5 to 10
Russet Burbank	5 to 15
Red Pontiac	7.5 to 12.5
Sebago	5 to 10
Kennebec	8 to 12.5
Irish Cobbler	8 to 12.5

The most recent results[13] in the United States come from the demonstration tour of the Portable Cesium Irradiator.[50,51] Prosser Packers, Inc., Prosser,

Variety:	*Dose:*	*T, °C:*	*Δt:*	*t:*	*Ref.:*
Russet Burbank	6.2 to 8.5, 7.6 to 10.8, 9.7 to 14.9 krads	Common, 2.2, 7.2°	2 days	182 days, 211 days	13

Wash., and Rogers Walla Walla, Inc., Walla Walla, Wash., evaluated irradiated potatoes and reported no sprouting 182 days and 211 days, respectively, after irradiation in any lots regardless of storage conditions (Figs. 4 and 5). Irradiated potatoes were shipped to Honolulu from Seattle; no sprouting occurred. Potatoes sent to Chicago by railroad also showed no sprouting.

Fig. 4 Storage of Washington State potatoes after 180 days at 45° (7.2°C) and 95% *R.H.* (From Ref. 13, courtesy of L. B. Bradley, Office of Nuclear Energy Development, Washington State.)

Fig. 5 Storage of Washington State potatoes after 211 days under common storage conditions. (From Ref. 13, courtesy of L. B. Bradley, Office of Nuclear Energy Development, Washington State.)

Canada

Of the Western nations, Canada has come closest to commercializing the radiation treatment of potatoes. Its research has been detailed; a demonstration program in 1961 to 1962 was very successful, and a commercial plant to irradiate potatoes and other products was opened. Unfortunately, the plant shut down after 1 year because the potato crop failed and there were no potatoes to be irradiated. Typical sprout-inhibition results are shown in Fig. 6.

Results of the first large-scale experiments were reported[52] in 1960. Sprouting results were covered by Parks.[53] Controls of both varieties stored at the higher temperature were well sprouted at 4.5 months of storage; control potatoes at the lower temperature showed short sprouts at 7 months. No irradiated potatoes had sprouted after 11 months of storage, although Netted Gem potatoes were in better condition than the Katahdin potatoes. Throughout the experiment, control potatoes at the lower temperature showed only slightly more weight loss than did the irradiated potatoes. At the higher storage temperature, control potatoes were discarded after 8 months; irradiated potatoes showed only 9% weight loss at that time. These results clearly justified further study of the problem. Errington and MacQueen[54] gave a popular-level presentation in which they stated that later research had shown that Katahdin and Russet Burbank varieties can be stored 8 months at 12.8°C after an 8-krad dose. They also reported a further experiment which showed that an 8-krad dose inhibits sprouting in each of 10 varieties of potatoes for at least 8 months

Variety:	*Dose:*	*T*, °C:	*t:*	*Ref.:*
Katahdin Netted Gem (Russet Burbank)	8 to 15 kRep	4.4 and 20°	11 months	52

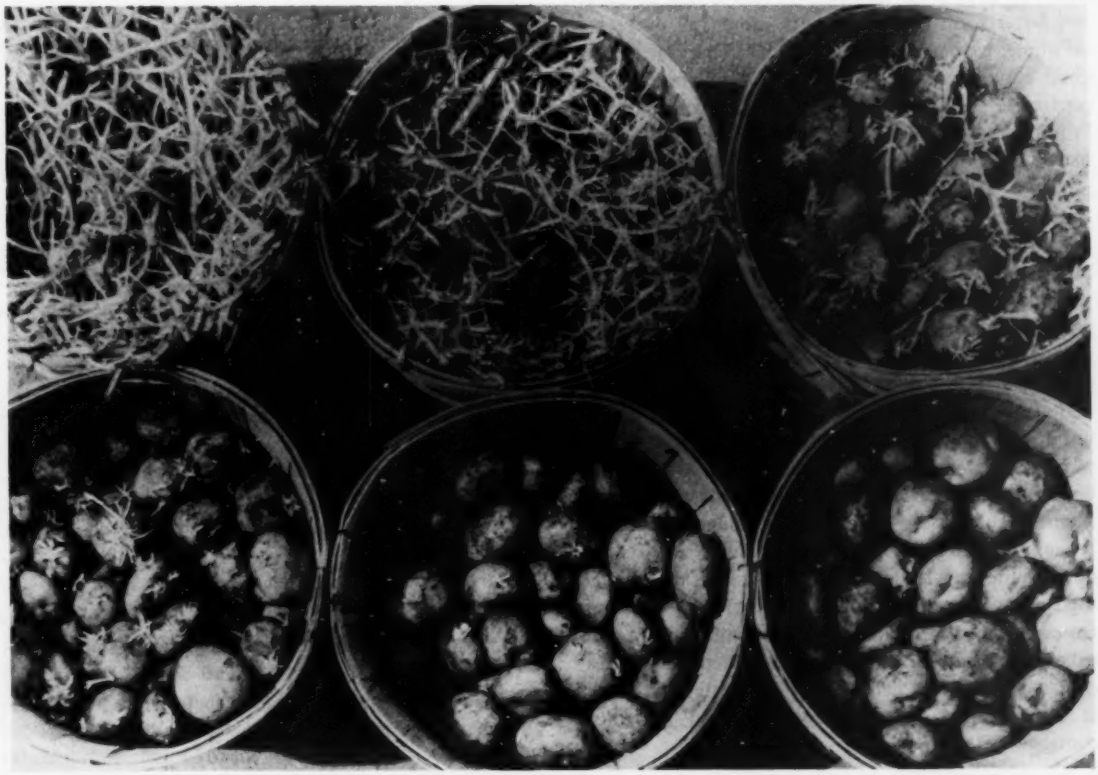

Fig. 6 Katahdin potatoes treated as part of the Canadian pilot scale demonstration program. Doses range up to 7.7 krads. These potatoes were stored 5.5 months at 12.8°C. (Courtesy of Atomic Energy of Canada Limited.)

under the heated storage conditions necessary in Canada during the winter. This article[54] and a subsequent article[55] gave preliminary details on the pilot scale potato irradiation demonstration program.

The pilot scale program[56] was carried out in Canada's four eastern provinces in 1961 to 1962; 26 members of industry cooperated. A mobile irradiator with an 18-kCi ^{60}Co source was used; an 8-krad dose could be applied to 2200 lb of potatoes per hour. Each industrial participant provided his own potatoes, which

Variety:	*Dose:*	*T, °C:*	*t:*	*Ref.:*
Katahdin Kennebec Cherokee Sebago Netted Gem Irish Cobbler	8 krads	Up to 26.7°	Up to 10 months	56

were cured before irradiation and were stored with controls under identical conditions after irradiation. The irradiated potatoes could be sold to the public in whichever form the participants chose, i.e., processed or whole. Kennebec, one of the six varieties tested, is a good chipping variety that is grown in three of the provinces. Sebago is the variety grown mainly on Prince Edward Island. Storage was in pallet boxes, bins, barrels, and bags. Eight of the 26 participants stored potatoes at high temperatures to minimize sugar content; the other participants placed potatoes in common storage. Sprouting was completely controlled in all cases. A field run was made in which special care was taken with handling to show that where there was no mechanical injury, curing potatoes before irradiation was unnecessary. MacQueen,[57] reporting on the entire Canadian food-irradiation program to an international symposium in 1964, stated that irradiation did not affect stored potatoes as much as did differences in varieties and storage conditions. He also said that in Canada special labeling of marketed irradiated potatoes is not required; this practice was thought to be fair because the use of chemical sprout inhibitors also does not require special labeling. Irradiation can best be used as a sprout-inhibition treatment when potatoes are cured, irradiated, and stored all in the same (4-ft)^3 pallet box. Use of a pallet box greatly reduces injuries caused by excessive handling, offers greater flexibility in storage, and makes temperature and humidity control easier.

Australia

Wills[58] irradiated Tasmanian potatoes in 1961 and 1962, using spent fuel elements the first year and ^{60}Co

Variety:	*Dose:*	*T, °C:*	*Δt:*	*t:*	*Ref.:*
Up-to-Date Kennebec Sebago Sequoia	5 to 16 krads	7.2 and 20°	10 weeks	6 months	58

the second year. A 5.5-krad dose inhibited sprouting of the Up-to-Date variety for 33 weeks; a 10-krad dose inhibited sprouting of Kennebec and Sebago varieties for 25 weeks. In 1962 the potatoes had begun sprouting by the time they were irradiated, but a 5-krad dose stopped this sprouting. Wills notes that these doses are lower than those reported elsewhere.

Belgium

Results from the Institut National pour l'Amelioration des Conserves de Legumes show that radiation inhibits sprouting of the Bintje variety.[59] However, the results were not consistent, probably because of nonuniformity of dose. The IRMA irradiator[60] with a ^{137}Cs source was used to provide a 10-krad dose to potatoes that had been cured for 6 weeks at 8°C.

Colombia

Potato production in Colombia is ~1.2×10^9 lb annually; spoilage ruins ~20%. In this experiment

Variety:	*Dose:*	*T, °C*	*t:*	*Ref.:*
Tocarrena Pardo Pastusa	5 to 15 krads	10°	8 months	61

control potatoes had to be discarded, but potatoes[61] irradiated at 7.5 krads or greater doses were in good condition.

Denmark

Truelsen[62] reported two experiments that had to be terminated when both irradiated and control potatoes became discolored. Although slightly higher

Variety:	*Dose:*	*T, °C:*	*Δt:*	*t:*	*Ref.:*
Bintje	6 to 12 krads	5, 10, 15°	1, 2, 4, and 6 months	8 months	62

doses were required as time between harvest and irradiation increased, 8 krads was an adequate dose in each case.

The literature review by Skou[6] (49 references) states that all doses greater than 2 krads have some inhibiting effect, but doses greater than 8 krads are required to completely inhibit sprouting.

Egypt

Abdel-al[63] reported that the crop harvested in May and June sometimes starts sprouting immediately because of the high temperatures in the Near East. All potatoes in this experiment had begun sprouting before

Variety:	*Dose:*	*T, °C*	*t:*	*Ref.:*
Alpha	8 to 14 krads	Common, 30 to 35°	6 months	63

they were irradiated. After 6 months the weight of sprouts per 100 g of potatoes was 9.25 g for the unirradiated controls but only 0.14 g for the 14-krad-treated potatoes.

England

In England and Wales losses to sprouting and enhanced water loss were probably ~30 kt/year in the early 1950s, according to Burton and Hannan.[64]

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*Δt:*	*t:*	*Ref.:*
Dr. McIntosh	2 to 35 krads	10°	78%	5 days, 55 days, 6 mo.	15 mo.	64
Arran Consul Craig's Defiance Golden Wonder Home Guard	8.5 krads	10°	78%	3 to 4.5 mo.	15 mo.	64

Extensive tests were undertaken, particularly with the Dr. McIntosh variety. Burton and Hannan concluded that a 3.5-krad dose gives a commercially acceptable result; this experiment and results have not been duplicated by others. Some sprouting occurred at all doses less than 8.5 krads, but the sprouts were very small—2 mm long. Larger doses killed existing sprouts and completely prevented additional sprouting. With varieties other than Dr. McIntosh, the 8.5-krad dose did not kill sprouts already well started. Burton and de Jong[65] state that inhibition varies widely with the variety and state of the potato and with the kind of storage. A 10-krad dose of 500-keV electrons caused no inhibition, but 11 krads from 200-keV X rays gave complete suppression. Gamma radiation is effective at 10 krads or smaller doses. The net result of irradiation—inhibition of sprouting—does not prolong storage indefinitely.

France

Vidal[66] has stated that a 5- to 6-krad dose is satisfactory for short-term storage, but a 7.5- to 10-krad dose is necessary for storage of 12 months or

Variety:	*Dose:*	*t:*	*Ref.:*
Saskia Bintje	5 to 15 krads	12 months	67

more. In a later experiment Vidal[67] claimed that 7.5 krads was almost completely effective, but he recommended 10 krads for industrial use. Sandret and Michiels[68] achieved lengthy storage under ideal conditions. Losses in irradiated potatoes are usually ~20% less than that of controls.

Variety:	*T, °C:*	*R.H.:*	*t:*	*Ref.:*
Bintje Kerpondy	10 to 12°	High	1.5 years	68

Germany, East

Buhr and coworkers[69] irradiated 19 varieties of potatoes and found that an 8-krad dose gave complete

Variety:	*Dose:*	*T, °C:*	*t:*	*Ref.:*
See Table 7	4 to 16 krads	4 to 18°	15 months	69

sprout inhibition. Table 7 presents an evaluation of the potatoes after 15 months of storage; the dose used was 16 krads.

Table 7 Evaluation of 19 Potato Varieties After a 16-krad Dose and Storage for 15 Months (Ref. 69)

Variety	Appearance	Variety	Appearance
Pirat	Very good	Ora	Satisfactory
Amsel	Very good	Sperber	Satisfactory
Li. 4987/54	Good to very good	Sagitta	Satisfactory
		Kastor	Poor
Gunosa	Good	Apollo	Poor
Stieglitz	Good	Spekula	Poor
Meise	Good	Pollux	Poor
Drossel	Good	Schwalbe	Very poor, rotten
Fink	Good		
Gerlinde	Satisfactory	Spatz	Very poor, rotten
Rotkehlchen	Satisfactory		

Germany, West

In one of his early food irradiation articles, Kuprianoff[70] mentions radiation sprout inhibition.

Patzold and Kolb,[71] early German researchers, found that a 4-kR dose inhibited but did not stop sprouting in the Bona variety; 8-kR and 16-kR doses stopped sprouting entirely, even after it had begun. On Vera

Variety:	*Dose:*	*T, °C:*	*t:*	*Ref.:*
Vera Bona Ackersegen	0.25 to 16 kR	2 to 14°	6 months	71

potatoes weight loss from unirradiated controls was 16.5%, but potatoes receiving an 8-kR dose only lost 0.6%. For the Bona potatoes the losses were 6.6% for controls and 0.4% for irradiated specimens. For the Ackersegen variety, controls lost 5.4% and irradiated potatoes lost 0.3%. Patzold and Weiss[72] stated that an 8-kR dose of gamma radiation from ^{60}Co gave lasting sprout inhibition and reduction of weight loss.

Gantzer and Heilinger[73] used an X-ray machine to inhibit sprouting in potatoes, and Berger and Wolf[74] suppressed sprouting with radiation from a Betatron. Hansen and Grunewald[75] compared inhibiting doses

Variety:	*Dose:*	*t:*	*Ref.:*
Corona Feldeslohn	4 kR		73
Heida	1 to 60 kR	30 weeks	74

for 14 varieties of potatoes (Table 8). More recent results from Scheid and Heilinger[76] confirmed the finding by Hansen and Grunewald that the Maritta variety is most difficult to prevent from sprouting.

Table 8 Sprouting Results on 14 Potato Varieties Stored 11 Weeks at 15°C (Ref. 75)

Variety	Percent sprouted at dose indicated			
	4 kR	8 kR	12 kR	15 kR
Anco	100	30	–	–
Arensa	5	–	–	–
Bona	5	–	–	–
Carmen	50	10	–	–
Cosima	30	–	–	–
Datura	90	40	10	–
Delos	100	20	–	–
Feldeslohn	60	–	–	–
Grata	70	–	–	–
Heida	70	20	–	–
Heiko	80	10	–	–
Isola	70	5	–	–
Lori	30	–	–	–
Maritta	100	80	30	5

Variety:	*Dose:*	*T, °C:*	*t:*	*Ref.:*
See Table 8	4 to 15 kR	15°	11 weeks	75
Maritta	3.2 kR	20°	10 days	76

India

Mathur[77] concluded that a 6-krad dose was optimum for Gola potatoes and a 9-krad dose for

Variety:	*Dose:*	*Δt:*	*t:*	*Ref.:*
Gola Up-to-Date	3 to 9 krads	2 weeks	4 months	77

Up-to-Date potatoes. Lewis and Mathur[78] established a 6-krad dose as optimum for the Phulwa variety. Mathur has also studied the effect of time after harvest before

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*t:*	*Ref.:*
Phulwa	6 krads	12° and 21 to 35°	85 to 90% 57 to 90%	10 months 5 months	78

irradiation, and he concluded that the nearer the potato is to the end of its dormancy period, the greater is the effect of radiation. Recently, Mathur[79] published results of studies with Up-to-Date seed potatoes. He attempted to extend their storage life by using a chemical treatment with correct time-of-irradiation and a dose that produced an effect that could be reversed with chemicals. Mathur established five periods of development during storage of potatoes: (1) pre-

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*Δt:*	*t:*	*Ref.:*
Up-to-Date	3.5 krads	9°	85 to 90%	Up to 16 weeks	Up to 44 weeks	79

dormancy maximum (time of harvest), (2) predormancy minimum (3.5 to 4.5 weeks after harvest), (3) dormancy (8.5 to 9.5 weeks), (4) prespouting minimum (13.5 to 14.5 weeks), and (5) sprouting (15.5 to 16.5 weeks). He concluded that a 3.5-krad dose given at the predormancy minimum stage and followed by a 50-min dip in a 500-ppM solution of the methyl ester of indolyl-3-acetic acid would result in a 44-week storage life for Up-to-Date seed potatoes (Table 9).

Dharkar[80] obtained a storage life of up to 6.5 months for Indian potatoes. Dharkar and Sreeni-

Variety:	*Dose:*	*T, °C:*	*t:*	*Ref.:*
Phulwa	6 krads	Room temp.	1.5 months	80
Up-to-Date	9 krads	10 to 12°	6.5 months	80

vasan,[81] reviewing India's food irradiation program at an international conference, stated that a 10-krad dose inhibits sprouting for 32 weeks at room temperature; unirradiated controls sprout at 8 weeks.

Table 9 Combined Effect of Radiation and Chemical Treatment on Up-to-Date Seed Potatoes Stored at 9°C and 85 to 90% *R.H.* (Ref. 79)

Developmental stage	Irradiation treatment	Postirradiation IAA treatment*	Mean storage life, weeks†
Predormancy maximum	None	None	17.0
	3.5 krads	None	12.5
	3.5 krads	Yes	22.0
Predormancy minimum	3.5 krads	None	25.5
	3.5 krads	Yes	44.0
Dormancy	3.5 krads	None	23.0
	3.5 krads	Yes	31.5
Presprouting minimum	3.5 krads	None	19.0
	3.5 krads	Yes	24.5

*A 50-min dip in a 500-ppM solution of the methyl ester of indolyl-3-acetic acid.

†Including the preirradiation period.

Israel

A preliminary report[82] of Israeli experiments on radiation inhibition of potato sprouting appeared in 1966, and full details were presented at two international conferences later that same year.[83,84] Because there are two crops each year for Middle Eastern countries, storage for more than 6 months is not needed. However, storage at ambient temperatures, which are high, leads to rapid sprouting. Most potatoes are stored at 4°C in relatively expensive refrigerated warehouses. The Up-to-Date variety accounts for 70%

Variety:	*Dose:*	*T, °C:*	*Δt:*	*t:*	*Ref.:*
Up-to-Date	6 to 14 krads	Ambient, 4, 8, 14°	8 weeks	Up to 12 mo.	84

of Israel's crop. At 24-week storage, controls at all temperatures were sprouting; 4 weeks after withdrawal from storage, all controls were 100% sprouted. The 10-krad dose reduced initial sprouting to 5 and 15% at 4 and 14°C, respectively, with almost no growth of sprouts during the ensuing 4 weeks. Under ambient conditions the 10- and 14-krad-treated lots were in good condition and were organoleptically acceptable after 24 weeks.

Italy

The Italian potato crop is ~4 x 10^6 tons/year; per capita consumption is ~50 kg/year (110 lb/year). Denti[85] has reviewed the possibilities for irradiation preservation of potatoes, but no work has been reported.

Japan

Ogata and coworkers[86] found that irradiation at the beginning of dormancy did not prevent sprouting,

Variety:	*Dose:*	*T, °C:*	*Ref.:*
Irish Cobbler	3 to 12 kR	Room temp.	86

although sprouts on potatoes irradiated at 7 and 12 kR did not grow further. The 12-kR treatment prevented sprouting on potatoes irradiated at the end of dormancy. A review[87] of Japanese food-irradiation studies recommended a 7-krad dose at the beginning of storage for the best results.

New Zealand

Unsatisfactory results were reported by McNaughton,[88] who suggested that excessive time between harvest and irradiation was the cause.

Variety:	*Dose:*	*T, °C:*	*Δt:*	*t:*	*Ref.:*
Ilham Hardy	7 to 20 kRep	21.1°	6 months	10 weeks	88
Chippewa					

Norway

Mikaelsen and coworkers[26] did some of the earliest work on radiation inhibition of sprouting of potatoes. Later they compared the effect of the chemical Fusarex, a tetrachloronitrobenzene compound, with radiation doses from a reactor.[89] Sprouts had already appeared on some potatoes; these died immediately

Dose:	*T, °C:*	*t:*	*Ref.:*
5 to 40 krads	4 to 6°	12 months	89

after 10-krad or greater doses. Potatoes irradiated at doses of more than 5 krads showed only a few primordial sprouts after 12 months. Mikaelsen and associates[90] found that a 5-kRep dose was not as

Variety:	*Dose:*	*T, °C:*	*t:*	*Ref.:*
Kerr's Pink	5 to 15 kRep	7° av., 14° av.	15 months	90

effective at high temperatures as a larger dose, but 5 kRep did give satisfactory results at low temperatures. After 12 months of storage, 15-kRep-treated potatoes lost the least weight; after 15 months these were the only potatoes still suitable for taste-panel testing, although they were very sweet.

Pakistan

Farooqi and coworkers[91] reported that controls lost 31.2% weight after 150 days, but 10-krad-treated

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*Δt:*	*t:*	*Ref.:*
Ultimas Holland	2 to 10 krads	28.3° av.	69% av.	15 days	210 days	91

potatoes lost only 14.3%. After 210 days only two potatoes of the 10-krad lot had to be discarded—a loss of 0.1%.

Portugal

The main variety grown in Portugal is Arran Banner; farmers grow it because of its high yield, but it

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*t:*	*Ref.:*
Arran Banner Condea Anco Claudia Arran Consul Desiree	10 krads			4 months	92
Arran Banner	5 to 15 krads	18 to 20°	70 to 80%		92

keeps poorly. Preliminary experiments[92] with this variety and others showed that a 10-krad dose stops sprouting after it has begun. In a later experiment with Arran Banner, a 5-krad dose allowed only slight sprouting; higher doses completely inhibited sprouting.

South Korea

Park and associates[93] reported that sprouting of 7.5-krad-treated potatoes was inhibited at a low storage temperature, but a 9-krad dose was required to inhibit sprouting at a high storage temperature.

Variety:	*Dose:*	*T, °C:*	*Δt:*	*Ref.:*
Irish Cobbler Saco Tachibana Warba Kennebec Shimabara	4.5 to 9 krads	Low High	1 week	93

Spain

In a general review of food-irradiation projects, Fernandez y Gonzalez[94] reported satisfactory sprout

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*t:*	*Ref.:*
Urgenta	5 krads	19 to 31°	60 to 80%	150 days	94
Alava Gineke	5 to 15 krads	10 to 25°	40 to 87%	9 months	95

inhibition. Garcia de Mateos Lopez and associates[95] chose a rapid-sprouting variety to thoroughly test irradiation. A dose rate of 520 krad/hr was used. Of the controls, 80% sprouted after 20 days and 100% after 3 months. Doses greater than 5 krads totally inhibited sprouting during the 9 months of the experiment. The dose recommended for industrial practice was 8 krads.

Sweden

Early results of Jaarma[96] showed the effectiveness of the method. Later, Jaarma[97] reported a study of several varieties; different dose rates from a ^{60}Co

Variety:	*Dose:*	*T, °C:*	*Ref.:*
Eva Bintje President	16 krads	5°	96

source and from an X-ray machine were used. Inhibition of sprouting is most pronounced if the potatoes are irradiated immediately after harvest, although there were considerable varietal differences. Larger doses are

Variety:	*Dose:*	*Δt:*	*Ref.:*
Bintje Early Puritan Eva President Primula Ulster Chieftain	10 to 20 krads	1-month intervals	97

needed as time after harvest increases. The results obtained with the X-ray machine are considered to be preliminary because the machine could not be used in any practical application. A dose of 15 krads with soft X-rays did satisfactorily inhibit sprouting, however.

USSR

At a USSR national conference in 1957, Metlitsky and coworkers[98] reported that a 10-krad dose inhibits sprouting in the Lorkh variety, but other varieties

require only 8 krads. After 1 year, total loss and wastage was only 10%. Rakitin and Krylov[99] reported results of studies using an X-ray machine. The 10-krad-

Variety:	*Dose:*	*t:*	*Ref.:*
Berlikhingen	10 or 40 krads	8 months	99

treated potatoes did not sprout and had a weight loss of only 11.8%; control potatoes were well-sprouted and had a total weight loss of 72.0%.

In 1959 Rubin and associates[8] published a comprehensive review of the use of ionizing radiation to inhibit sprouting of potatoes; they cite 113 references, of which 59 are to Russian work. Although 10-krad-treated potatoes will not sprout, this is not necessarily the optimum dose. The minimum dose necessary to maintain resistance to microorganisms while preserving the nutritional value should be used. Lorkh potatoes irradiated at 8 kR had weak shoots after 12 months of storage; complete inhibition was obtained with 10 kR. The effect of radiation is greater at different stages of storage; potatoes irradiated December 1 and planted April 27 sprouted 36 days later, but potatoes from the same harvest that were not irradiated until April 15 and planted April 27 did not sprout until 53 days later.

Variety:	*Dose:*	*Δt:*	*t:*	*Ref.:*
Lorkh Berlikhingen Priekul'skii Epron Seyanets 9729/Ukhtomskii Rannyaya roza Moskovskii Peredovik	2 to 10 kR	Various	12 months	8

Maximum sensitivity to radiation does not occur at the same time in all varieties. The Moskovskii potatoes showed greatest sensitivity during, rather than at the end of, dormancy. Epron and Peredovik varieties were more sensitive during dormancy, but Priekul'skii and Berlikhingen were more sensitive when the eyes sprouted. Some varieties are more sensitive than other varieties regardless of stage of dormancy. The Rannyaya roza, Moskovskii, Peredovik, and Lorkh varieties require lower doses to inhibit sprouting than do the Epron or Berlikhingen varieties.

Rubin and Metlitsky[100] stated that the recommended dose is 8 kR, but Krushchev and associates[101] stated that 10 krads is the usual dose. Krushchev and associates also pointed out that the dose needed can vary with the time of use of the potatoes. Potatoes to be used in April should be given a 3-krad dose in October; potatoes to be used in June should be given a larger dose in November.

Krushchev and coworkers[101] cite Metlitsky's work[18] as being the world's first on radiation sprout inhibition of potatoes, but Rubin and associates[8] imply that Metlitsky's work involved only onions. However, Metlitsky was a coauthor of both papers; the confusion may be in the translations.

Work with ^{60}Co and with 620-MeV protons was reported by Shaidorov and coworkers.[102] The inhibitory effect was stronger when radiation was directed onto the eyes than onto the whole tuber; the effect of protons was much stronger than that of gamma rays.

Variety:	*Dose:*	*Δt:*	*t:*	*Ref.:*
Lorkh	5 to 15 krads	2 weeks, 5 months, 7 months	13 months	103

Metlitsky and others[103] found that irradiation 2 weeks after harvest gave excellent storage results; some of the potatoes used in their experiment were eaten as long as 13 months after irradiation.

Venezuela

Solanas and Darder[104–106] found that a 5-krad dose is sufficient to inhibit sprouting for short-term

Variety:	*Dose:*	*T, °C:*	*R.H.:*	*t:*	*Ref.:*
Katahdin	1.25 to 20 krads	10 to 22°	60 to 95%	8 months	106

storage. These authors point out that determination of the optimum dose is important, because the cost of treatment depends on the dose required to inhibit sprouting.

Other Countries

Poland and the Union of South Africa are both reported to have programs on potato irradiation.[5,10] However, no actual references to work in either country were found in the available literature. A 1963 Polish book[107] on food irradiation, which contains several pages on sprout inhibition of potatoes, cites 30 references on potato irradiation—but not one to Polish work.

South American countries other than Colombia and Venezuela are known to be studying potato sprout inhibition,[108] with the general result given that an 8- to 10-krad dose will inhibit sprouting for 8 months.

Summary of Results

The results obtained by the researchers cited above would indicate that, in general, the best results of irradiation of potatoes are obtained when top-quality potatoes are dug, cured for a period (ranging from 2 to 10 weeks), and irradiated to a dose of 8 to 10 krads. If possible, preculled potatoes should be cured, irradiated, and stored all in the same container—to minimize handling damage and handling costs. Where care is taken to avoid cuts and bruises during harvest and handling, curing may not be required. Temperature of storage is governed more by the intended end use of the potatoes than by any other criterion, but the optimum temperature of storage seems to be 45°F (7.2°C). Humidity and air movement should be the same as for nonirradiated potatoes.

Results cited in the above section that are particularly at odds with this summary would include Wills,[58] Burton and Hannan,[64] Ogata et al.,[86] and Jaarma.[97] Wills[58] admits that good results were obtained at doses lower than those usually used, but no explanation for this variation was given. The other three references are all to early work in this subject, when differing results might be expected.

EFFECT OF DOSE RATE

Several researchers have observed that a dose delivered at a high rate is more effective than the same dose delivered at a low rate. Jaarma[97] reported that in three of six potato varieties a dose rate of 600 krads/hr was more effective than a dose rate of 100 rads/hr. Krushchev and associates[101] reported on potatoes given a total of 5 krads at dose rates of 40 and 630 rads/min and then planted. The potatoes irradiated at the lower rate sprouted in 28 days, but the potatoes irradiated at the higher rate did not sprout for 53 days.

Kahan and Temkin-Gorodeiski[84] used two different dose rates—19 and 76 krads/hr—but did not discern any rate effect. This dose-rate variation is smaller than the variation in the two previous works[97,101] (1 : 4 compared with 1 : 6000 and 1 : 16). Mathur[77] found a high rate to be more effective than a low rate at a dose-rate ratio of 1 : 12. Although the total doses used by Scheid and Heilinger[76] were not high enough to effectively inhibit sprouting, they did record a dose-rate difference; 45 R/min was more effective than 4 R/min.

Except for a mention in Freund's review,[7] no dose-rate effect was reported by experimenters in the United States or Canada.

CHEMICAL SPROUT INHIBITORS

Maleic hydrazide (MH or MH-30) and isopropyl N-(3-chlorophenyl)carbamate—also referred to as chloro-isopropyl carbamate and abbreviated in both cases as CIPC—are the two chemicals most widely used in the United States for sprout inhibition of potatoes. Tetrachloronitrobenzene (Fusarex) compounds and the methyl ester of α-naphthalene acetic acid (MENA) are also used. Fusarex is used in Norway.[26,90] In the USSR,[8] CIPC and a dust that contains 3.5% α-naphthyl methyl acetate are used. In Spain,[95] MH, CIPC, and derivatives of 2,4-D acid are used. Canada has authorized the use of both MH and CIPC, although the latter is not allowed on table stock. France, on the other hand, in 1956 expressly forbade the use of chemical sprout inhibitors.

Sawyer and Dallyn[37] investigated tetrachloronitrobenzene, isopropyl N-phenyl carbamate, CIPC, MH-30, and MENA. At that time they concluded that CIPC and MENA were the most promising chemical inhibitors. However, they apparently applied MH-30 to stored potatoes after harvest; it is usually applied as a spray on the foliage before harvest, with good results.

All these chemicals inhibit sprouting in stored potatoes to some degree. Both MH-30 and CIPC are effective for 1 year on potatoes stored at 50°F (10°C). According to Freund,[7] both prevent potatoes in common storage from sprouting until the following June. For nearly any circumstance, chemical sprout inhibitors exist that are effective. However, neither chemical sprout inhibitors nor radiation can take the place of proper storage management; they only supplement good storage practices.

Advantages and Disadvantages

The Russians[101] state that most chemical preparations have a specific odor, and they characterize dusting as extremely laborious and unpleasant. Freund[7] states that among the advantages of chemical inhibitors the most important is that the time of application is not especially critical. Treatment with either CIPC or MH-30 has no effect on sugar accumulation, color, or texture.

Maleic hydrazide is applied in the field, which lessens storage requirements considerably. It does not interfere with wound healing; and, because MH-30 translocates to the interior of the potato, there is no problem of compliance with limits on external residues, although FDA has set 50 ppM as an internal limit. This compound is used extensively by farmers who grow potatoes under contract and know in

advance that long-term storage will be required. One disadvantage of MH-30 is that it must be applied at exactly the right time (2 to 3 weeks after full bloom); early application may reduce crop yield and late application may give incomplete sprout inhibition. Uniformity of treatment is important and sometimes difficult to obtain; for 24 hr after application, the atmosphere must be free of rain or heavy dew. Because its application must precede harvest, MH-30 may be used needlessly sometimes by a farmer whose crop is later bought for immediate use; this is an economic disadvantage of MH-30.

Application of CIPC to potatoes in bulk storage is simple. The warehouse must be made airtight. The chemical is then circulated through the potatoes. If the storage facility has a mist generator, that is used; a mist generator made from a wartime smoke-screen generator[109] is used by one custom fogger. The building is left sealed for 48 hr; fans keep the mist circulating. In many areas of the country, storage facilities do not have good air-distribution systems, and in such facilities, CIPC or other gases cannot be used effectively. The main drawback with CIPC is that inadequate distribution—caused by dirt, vines, trash, or poor air circulation—leads to poor results. A residue level has also been established for CIPC. It is perhaps the strongest chemical inhibitor available at the present time. However, this compound can increase rot if applied to new potatoes because it affects wound periderm formation; CIPC should not be applied until after curing. The evidence is contradictory, but there are some indications that potatoes treated with CIPC are susceptible to internal sprouting, which renders them unfit for use—especially for processing.

Fusarex is not as strong an inhibitor of sprouting as CIPC, but it has been used with good results on Long Island, N. Y. For best results it should be used in a good storage facility where the temperature can be kept at 50°F (10°C) or less. When used as a mist, it has the same drawbacks as CIPC in that it requires a good air-distribution system to be properly effective. Fusarex is the only sprout inhibitor that can be used on seed potatoes. Because it volatilizes rapidly at higher temperatures when used as a dust, Fusarex dissipates rapidly in the warm, moist soil air and allows the seed potatoes to sprout.

COMPARISON OF CHEMICALS AND RADIATION

Few direct comparisons of chemical sprout inhibition with radiation inhibition exist in the literature. Mikaelsen and associates[26] reported a 3.6% weight loss in potatoes treated with Fusarex and a 4.5% weight loss in 10-kR-treated potatoes after 8 months; neither group sprouted. Later, Mikaelsen and Roer[89] reported that Fusarex-treated potatoes started sprouting before irradiated potatoes. After 12 months of storage, both Fusarex-treated and control potatoes looked unsuitable for food, but irradiated potatoes were still acceptable. When planted, the Fusarex-treated potatoes sprouted 1 week later than did the controls; potatoes irradiated at more than 5 kR did not germinate. These Norwegian researchers[90] have indicated that Fusarex applied at double the recommended strength gave sprouting protection equal only to about a 5-kR dose of gamma radiation.

During the Canadian pilot-scale demonstration program, internal sprouting was observed in potatoes treated with an unidentified chemical inhibitor.[56] More specifically, Gardner and MacQueen[110] noted internal sprouting in Kennebec potatoes, to be used for chips, that had been treated with CIPC. Also during the pilot-scale program,[56] shrivelling and softening of both MH-30–treated and irradiated potatoes occurred toward the end of storage at high temperatures. However, this softening occurred only in the surface layer of irradiated potatoes; it was uniform throughout the MH-30–treated potatoes.

In Belgian work,[59] potatoes treated with CIPC were compared with the irradiated potatoes. Although numerical results were not given, evidently the irradiated potatoes were sufficiently better to warrant continuation of the work.

A specific study was carried out by Kwiat[111] to compare irradiation, CIPC, and MH-30 for treatment of Kennebec, Pontiac, and Russet Burbank potatoes. Although many factors were evaluated in this study, the degrees of sprouting after 1 year at 55°F (12.8°C) and 75% *R.H.* show that CIPC and irradiation (7.5- to 15-krad dose) were both superior to MH-30. For lower storage temperatures, the effects of the treatments differed little; in fact, the control potatoes were still acceptable for some process uses 8 months after harvest. Irradiated Pontiac potatoes were marginally better than CIPC-treated Pontiacs, but the reverse was true for Kennebec potatoes. The Russet Burbank potatoes were not chemically treated; only irradiated and control potatoes were compared.

In the results given by Bradley,[13] irradiated potatoes had not begun to sprout 211 days after irradiation. He pointed out that control potatoes treated in January with a chemical—presumably CIPC—had

also not sprouted under the excellent storage conditions used [45°F (7.2°C) and 95% *R.H.*].

HOW RADIATION INHIBITS SPROUTING

Exactly how radiation inhibits sprouting of potatoes was largely ignored by early researchers. Indeed, the literature on radiation inhibition of sprouting is remarkable for this very obvious lack of information. The proceedings[28] of the Brookhaven Conference contain no mention of the mechanism.

Metlitsky and associates[98] state that inhibition results from a combination of factors: change in state of cellular colloids; alkalization of cellular sap in meristematic tissue; and suppression of nucleic acid synthesis, oxidative enzyme activity, and respiration. Brownell and coworkers[42] suggest that irradiation disturbs the dividing mechanism or the metabolic systems of the sprout cells without affecting the metabolic processes of the cells in the potato itself.

Extensive Russian work, reviewed by Rubin and colleagues,[8] at first concentrated on the differences in respiration between irradiated and control potatoes; nothing directly affecting the sprouting mechanism was discovered. In cognizance of the extreme sensitivity of nucleic acid synthesis to radiation, the work was reoriented. These researchers thus established that potatoes lose the ability to sprout because irradiation inhibits nucleic acid synthesis in the apical meristems and alters the oxidation–reduction equilibrium. These changes are manifested by shifts in the *p*H of the interior of the cells and in the isoelectric point of the plasmatic colloids.

Previously (in 1958), Rubin and Metlitsky[100] had reported that retardation of germination in potatoes is governed by a combination of changes: (1) changes in the state of the cell colloids; (2) shift of isoelectric zone of albumens and nucleoproteins to the acid side; (3) retardation of synthesis of nucleic acids in the buds; and (4) suppression of activity of a number of oxidizing enzymes in the mitochondria.

Although the Russian work was still not widely known, Jaarma[97] stated in 1960 that sprout inhibition is the result of a disturbance of the phosphorylating mechanism. In 1963 Mathur[112] cited radiation inhibition of the endogenous indolyl-3-acetic acid synthesizing system, which he found could be reversed by dipping potatoes in a 1000-ppM solution of indolyl-3-acetic acid.

Freund, in his review,[7] stated simply that the basic cause of sprout inhibition by radiation is the decreased activity of vital nucleic acids. He cited Rubin and Metlitsky[100] to support this statement.

In the 1967 review by Metlitsky, Rogachev, and Krushchev[113] of all Russian food-irradiation work, the exact connection between potato respiration and sprout inhibition was given. Energy is stored in the cell in special phosphorus compounds, such as adenosine triphosphoric acid (ATP), by oxidative phosphorylation. Nucleic acid synthesis is suppressed by disrupting ATP synthesis; radiation breaks the chain between respiration and phosphorylation. The energy for nucleic acid synthesis is thus dispersed, and the potato cannot sprout.

SUMMARY

This first article in a planned three-article series on sprout inhibition in potatoes by radiation has given the early history of research into this phenomenon and summarized international results accumulated in the 16 years since Sparrow and Christensen[19] first aroused interest in this new way to extend the storage life of one of the world's most important food crops. A brief comparison to chemical inhibitors on the basis of effectiveness has been given, and the explanation that is now accepted for the phenomenon has also been presented.

When potatoes are irradiated, more than just the sprouting mechanism is affected. The vitamin, sugar, and starch contents are changed, and cell structure is altered. The potato resistance to microorganisms may also be affected. All these modifications bear on subsequent uses of irradiated potatoes. Cooking properties, e.g., suitability for chip manufacture, are of concern, as are the usual subjective organoleptic qualities. The second article in this series, planned for a subsequent issue of *Isotopes and Radiation Technology*, will summarize these radiation effects on the potato.

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POTATO-IRRADIATION SYMPOSIUM IN BRUSSELS

A symposium sponsored by several organizations, including the International Atomic Energy Agency, on irradiation of potatoes to prevent sprouting during storage was held in Brussels on Oct. 1–2, 1969. Some fifty representatives of government and industry participated. Three different panels discussed the subject from the standpoints of scientific and technological problems, economics, and wholesomeness of the product. Problems still to be solved include determination of varieties best suited to radiation processing, radiation-induced changes in biochemical composition of the tubers, and the culinary and nutritional properties of the irradiation product. Costs were estimated to be somewhat greater than for chemical treatment, but, at the same time, irradiation was considered more effective and convenient and more readily adaptable to automation. The consensus was that inhibition of sprouting by use of ^{60}Co or ^{137}Cs gamma radiation is entirely without danger to the consumer.

A subsequent meeting on November 3 of experts in the field outlined a tentative program to be followed in the European Community in further potato-irradiation methodology and testing. (MG)

A Proposed Method for Testing the Possibility of a Botulism Hazard in Radiation-Pasteurized Fish

By L. J. Ronsivalli,* M. S. Schwartz,† and J. T. R. Nickerson‡

Supplementary Keywords: *food preservation; industry; industry, food; seafood; wholesomeness; microbiology; theory; statistics.*

Editor's Note: This proposal is being published to evoke constructive criticism of the method. No technique is accepted at present to resolve the question of the possible botulism hazard in radiation-pasteurized fish, a question that must be answered if the process of irradiating seafood is ever to reach commercial use. Please direct comments to Mr. Ronsivalli (see address in footnote).

Abstract: *The promise of economic savings from the use of ionizing radiation to preserve fish is weakened by the uncertainty as to whether or not this treatment allows botulinum Type E toxin to develop before the consumer rejects the product because of obvious spoilage. The test proposed here compares the specific time at which the consumer can detect spoilage in either irradiated or nonirradiated fish with the specific time at which toxin develops in the products. The available data indicate that this test can determine whether or not a botulism hazard exists.*

Research[1] begun in June 1951 indicated that ionizing radiation at levels of less than 1 Mrad could be used to pasteurize foods. As a result of subsequent work, Proctor et al.[2] reported that the pasteurization of marine products by ionizing radiation was especially promising, and projects[3] were outlined for studying aspects of radiation preservation at various laboratories. Since 1960 many researchers have investigated and established the feasibility of pasteurizing marine species with low levels of ionizing radiation.

Technological advances in radiation processing have been paralleled by an increased understanding of the microbiological implications of the process. As a result, two consequences of pasteurizing fish (by radiation or *any* other means) have caused concern. Both relate to the possible development of toxin by *Clostridium botulinum* Type E.

1. When fish are pasteurized, most of the spoilage bacteria (pseudomonads) on the fish are destroyed. This destruction is believed to delay or to eliminate the development of the typical objectionable, odoriferous compounds normally associated with spoiled fish. The presence of pseudomonads is also believed to interfere with the growth of *C. botulinum* Type E. As a consequence of pseudomonad destruction, then, fish might spoil from nontypical microflora and might contain toxin.

2. If any benefit from pasteurization is to be retained, the fish must be packaged in such a way as to prevent their being recontaminated. Thus another consequence of pasteurizing fish is that, in the absence of "competitive" bacteria and in the confines of a package, the possibility is presumably enhanced that the spores of anaerobic pathogens (some of which survive pasteurization) will vegetate and produce toxin, especially if the product is mishandled. Although the degree of anaerobiosis in any given package environment depends inversely on the permeability of the package to air, localized sites of anaerobiosis can develop even in pouches made of materials that are highly permeable to gases, e.g., polyethylene.

Because the anaerobe *C. botulinum* Type E grows at relatively low temperatures (it will grow at temperatures maintained in most domestic refrigerators[4]), because it has been reported to be present in marine species,[5] and because the shelf life of fish can be extended several times by the destruction of spoilage bacteria by radiation, there is some concern that radiopasteurized fish might develop botulinum toxin before recognizable spoilage occurs, should the product be mishandled. However, the doubt which existed earlier—that radiopasteurized fish undergo typical spoilage (proteolytic breakdown)—has been shown to be unfounded.[6]

In view of the preceding discussion and because of the present regulations, approval for a new preservation

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technique that does not conform to the 12-D concept* will require a demonstration that the process does not constitute a hazard to public health. The purpose of this report is to describe a test designed to evaluate whether or not a botulinum Type E hazard exists in fish fillets pasteurized with gamma radiation. The test is based on a comparison of the interval (i.e., safety margin) between the time that spoilage is detected and the time that toxin is produced in both inoculated and uninoculated *irradiated* fillets and in both inoculated and uninoculated *nonirradiated* fillets. The first part of the report describes the test procedure and its underlying rationale; the second part describes the safety factors inherent in the test design.

TEST PROCEDURE AND RATIONALE

The proposed test procedure consists in three steps: (1) measurement of the time required for irradiated and nonirradiated fillets to develop the odors of spoilage; (2) measurement of the time required for toxin to develop to the threshold level in inoculated irradiated and nonirradiated fillets; and (3) analysis of the data—i.e., a comparison of the times observed in steps 1 and 2 to get a measure of the safety margins of both irradiated and nonirradiated fillets.

Time Required for Spoilage-Odor Development

Two controllable major variables that affect the shelf life of irradiated fish are the storage temperature and the amount of radiation absorbed. (The gaseous composition of the headspace in the package has also been shown to be important. The critical contributing characteristic of the package is its permeability to gases. For impermeable packages, whether or not a vacuum is applied is most important. The shelf life of the product is increased as the gas-barrier property of the package is increased. For the purpose of this test, the assumption is made that the same packaging materials and conditions are used throughout.) The samples should be stored, therefore, at a sufficient number of temperatures to permit the effect of any temperature within the desired range to be obtained by interpolation, and the samples should be irradiated at practical levels. Nonirradiated controls should be included in the experiment.

*The 12-D concept is the generally accepted belief that any process for sterilizing foods must be able to reduce the number of spores of resistant Types A and B *C. botulinum* through 12 log cycles, i.e., to 0.0000000001% of whatever contamination exists.

At present, the organoleptic panel is the most reliable analytical tool for determining when fish spoil. The panel will reject the fish when a sufficient amount of malodorous compounds has accumulated in them. By the time the nonirradiated fish develop an objectionable odor, the total plate count, which is largely of nonpathogenic organisms, will have become as high as 10^6 to 10^7 organisms per gram of fish. Figure 1 shows a typical growth curve for bacteria; line A indicates the approximate time that nonirradiated fish might become objectionable because of accumulation of malodorous compounds. The area under the curve is an expression of the bacterial activity, a portion of which produces the spoilage compounds.

Although threshold values (minimum concentration of an odoriferous compound which can be detected) vary among people, the range of these threshold values should occur in a small interval of time because of the nature of the bacterial growth curve—provided that all people can, in fact, detect spoilage odors. That is, although time increases

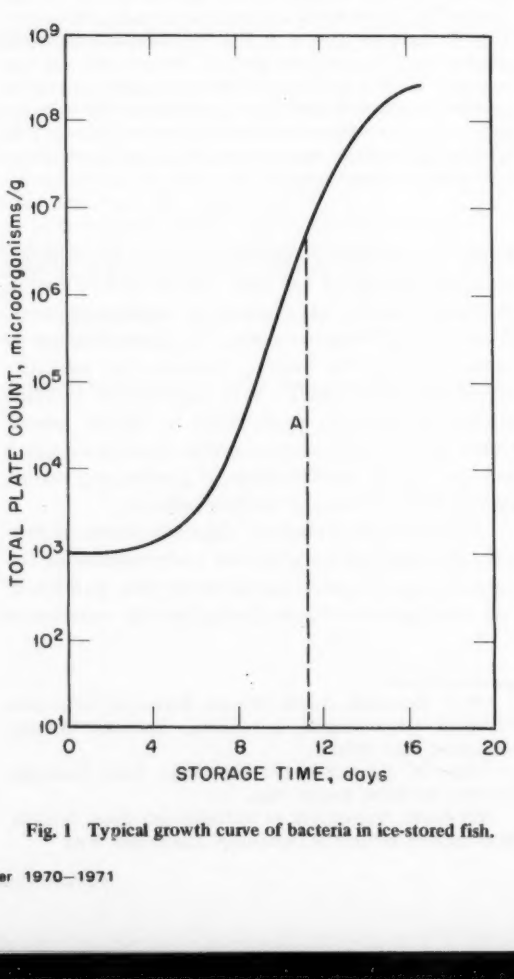

Fig. 1 Typical growth curve of bacteria in ice-stored fish.

linearly, the concentration of spoilage compounds apparently increases exponentially. The final sensory effect, however, may be linear, as indicated by the Weber–Fechner law of sensation* or by its restatement by Stevens.[7]

Data indicate that, although the threshold differs at which various individuals detect the odor of spoilage, the interval is short between the time when the most sensitive expert individual decides that a sample is spoiled and the time when the least sensitive expert individual decides that it is spoiled. Learson and Ronsivalli[8] found only a small spread in time (1 to 2 days) if the individuals were trained judges of spoilage but a much longer spread if the individuals were untrained.

In any group of consumers, however, some individuals may continue to accept spoiled fish for an unusually long time, either because they cannot detect the odor of spoilage or because they do not find the odor objectionable. Evidently such consumers are constantly in danger of eating spoiled or even toxic foods. Nevertheless, they must be considered in this work. The data from these unusual individuals, especially, and other panelists as well should be used only when they test *both* irradiated and nonirradiated samples.

In work at the Bureau of Commercial Fisheries Technological Laboratory at Gloucester, Mass., a sample is termed spoiled when it is unanimously rejected, in two consecutive tests, by an inexpert panel of about 20 individuals. For evaluation, the samples are coded and presented as raw products to the members of the panel, who are asked to either accept or reject the samples. When the time elapsing from complete acceptance to complete rejection is measured in this way, the shelf life of the sample is estimated with the greatest accuracy (see Analysis of Data, p. 214).

Time Required for Toxin Development

For experimental purposes, samples must be inoculated with spores of *C. botulinum* Type E to ensure the presence of this organism for the measurement of toxin-development time.

Inoculation of samples with spores at the same concentration that occurs in nature is desirable because the period of time required for toxin to develop is a function of the concentration of the inoculum. (The use of natural cultures rather than laboratory-bred cultures is also desirable.) No one knows, however, exactly what concentrations of spores occur in nature. Goldblith and Nickerson[9] reported a natural incidence of *C. botulinum* Type E on haddock (*Melanogrammus aeglefinus*) to be a maximum of 0.17 spore per gram of haddock.

To determine the relation between inoculum levels and toxin-outbreak time, the experimenter should inoculate samples at the naturally occurring level (which should be investigated more fully) and at multiples of this level to ensure that he has covered all possibilities. On the basis of the only quantitative data available on the concentration of *C. botulinum* Type E, the inoculum levels should therefore be, for example, 0.17, 1.7, 17, and 170 spores/g. These levels should provide safety factors of up to 1000.

Under the auspices and coordination of the Division of Biology and Medicine of the U. S. Atomic Energy Commission, several researchers have now investigated the time required for the development of toxin in haddock fillets.[9–11] Typically, these researchers prepared spores to be used in inoculations by incubating pure cultures of various strains of *C. botulinum* Type E (Beluga, Minneapolis, 8-E, and Detroit) at 50 or 85°F (10 or 29.4°C) in trypticase-peptone-glucose broth that contained a small amount of sodium thioglycollate. The spores were collected at the peak of sporulation by centrifugation and were refrigerated in distilled water until they were used. Just before use, some of the spores were given a heat-shock treatment and some were not. Their concentrations were determined on trypticase-peptone-glucose agar that contained small amounts of sodium thioglycollate and yeast extract. Haddock fillets were then inoculated at levels of 10^2, 10^4, and 10^6 spores per gram of fillet and stored at various refrigeration temperatures. At intervals of storage the inoculated samples were tested for the presence of toxin by the mouse-injection method.

The inoculum levels used by these researchers were many times higher than that apparently found in the natural environment; even the lowest level used (10^2 spores/g) represents a safety factor of more than 500 according to the incidence levels of spores reported by Goldblith and Nickerson.[9]

The final interpretation of the proposed test is based on a comparison of "safety margins" in radiopasteurized samples and in nonirradiated samples. For a given sample, the margin of safety is the interval between the time that spoilage is detected and the time that toxin develops.

*The Weber–Fechner law states, essentially, that the intensity of a stimulus must increase logarithmically to produce a linear increase in the corresponding biological response.

Analysis of Data

Variability in the Data. From the analytical point of view, data collected on the storage life up to spoilage of both irradiated and nonirradiated fish vary in several ways. Because one fish varies from another, for example, one lot of fish varies from another lot. This variation may be relatively small, however, when compared with the variation in the ability of consumers to detect spoilage, particularly when those consumers have not been trained to judge the freshness of fish.

To these largely random variations are added the planned variations in levels of radiation and in temperature of storage. The random errors must be isolated and their magnitudes must be estimated so that the effect of the planned variations on storage life can be studied.

Similarly, measurements of botulinum toxin vary. Unfortunately, the currently available data have not been based on a sufficient number of test animals or on an adequate frequency of testing to lend themselves to effective statistical evaluation. (The method used to measure the development of toxin should provide MLD_{50}* data, as did Schantz.[12])

Data Curves. Figure 2 compares the curve for a panel that is expert in detecting spoilage with the curve

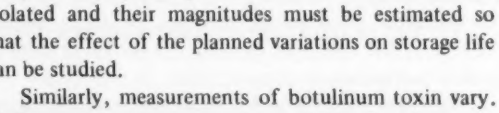

Fig. 2 Rejection rates by expert and inexpert panels of haddock fillets stored at 33°F (0.6°C).

for an inexpert panel. (Learson and Ronsivalli[8] have described how to train a panel to be expert and how to determine its reliability.) Note that both curves are sigmoid shaped. Because the toxin-development data presently available are not usable, only a theoretical plot of toxin-outbreak data is given (Fig. 3). This theoretical plot is in agreement with the work of Schantz,[12] who used the same statistical method proposed here in his assay of botulinum toxin. To yield statistically analyzable data, future experiments on the development of toxin must include more mice per test and more frequent testing with the mice. The resulting data should then follow a normal biological-response distribution.

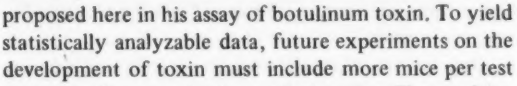

Fig. 3 Theoretical lethality rate of mice from increasing concentrations of botulinum Type E toxin in inoculated fillets. (The increase in concentration of toxin is related to the increase in time.)

From the standpoint of analysis and interpretation, the graphs that show spoilage time and toxin-formation time are remarkably similar; each curve is sigmoid shaped. Unfortunately estimating the elapsed times to the point of spoilage and to the point of toxin development by means of sigmoid curves is difficult because each curve asymptotically approaches the line that indicates the complete rejection of a sample or the deaths of all the mice.

Fortunately, however, these sigmoid curves can readily be analyzed statistically through maximum-likelihood methods,[13] in which a form of probit analysis or normal equivalent deviate analysis is used. The use of conventional statistical parameters (such as the standard deviation) or conventional statistical tests (such as the t test) assumes a rough correspondence of the data with the normal distribution. Probit analysis investigates this assumption explicitly, and conclusions based on the results from this analysis are reinforced by the knowledge that the form of the data distribution has been determined, not assumed, and, where immediate deductions are possible, agreement with normality has been established. The use of a form of probit analysis is well known to investigators of drug properties. In these cases, *Response* (*y*-axis) is plotted

*The amount of toxin that will kill 50% of the mice within the specified period for Type E toxin.

against *Dosage of Drug* (*x*-axis), and results are often summarized by the *x for* R_{50}—i.e., *dosage for 50% response.* The shape of a typical dose-response curve is that of Fig. 2 or 3. The *x for* R_{50} is the chosen method of reporting potency for drugs because the *100% Response* region (corresponding to the right half of either Fig. 2 or 3) is just that part of the curve which is most unreliable. Essentially the same situation exists with respect to maximum shelf life.

The statistical difficulty with determining the shelf life is that the tail of the sigmoid curve extends to infinite time in a strict mathematical sense. Practically, it stops short of infinity, whatever the mathematics might say, but exactly where the tail stops short is never easy to tell empirically, and statistical analysis flounders in attempting to decide this point. That is, the 100% rejection point (shelf life) is not known accurately; a large error is associated with its determination. The RT_{50} (50% rejection time), on the other hand, is just that point in time which is determined most sensitively and with greatest accuracy. Thus from knowledge of the RT_{50}, the point of 100% rejection (or 99.99. . .% rejection) can be estimated by taking RT_{50} + three standard deviations or RT_{50} + four standard deviations, etc. The standard deviations necessary for these estimates are also determined from data plots such as Fig. 2.

Both the form of the sigmoid curve and the method of its analysis hold for the estimation of beginning time of botulinum toxin development as well as for the estimation of shelf life. In both cases, estimations of the relevant parameters from Figs. 2 and 3 are simplified by use of a probit transformation of the percentages plotted on the *y*-axes of the figures. Application of the probit scale simply means that each percentage value is translated into a new value called the probit of the percentage. The effect of the probit transformation is something like that of a logarithmic transformation. (Indeed, the probit value corresponding to a percentage value is looked up in a probit table, much as the logarithm of a number is looked up in a table of logarithms.) In particular, if the data on shelf life or on toxin development are consistent with a normal distribution, then the cumulative normal distributions, which are sigmoid in shape, are transformed to straight lines (Figs. 4 and 5). Not only is the straight line easier to interpret by eye, it also allows for easier estimation of RT_{50} (time for 50% rejection or 50% spoilage) and TD_{50} (time for 50% toxin development). Thus probit analysis offers a convenient method for testing the assumption of quasi normality (i.e., consistency with the normal distribution) which characterizes much of the conventional statistical approach to data analysis. Furthermore, when normality of distribution is indicated, probit analysis then permits the convenient and accurate estimate of such parameters as RT_{50}, together with relevant standard deviations and associated confidence intervals.

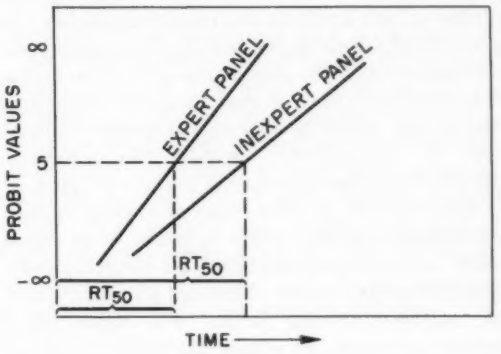

Fig. 4 Probit transformation of the rejection-rate curves shown in Fig. 2.

Details of the analysis can be found in the appropriate monographs (for example, Finney[13]). The RT_{50} is the point on the probit line that corresponds to the probit 5 value; estimates of the standard deviation are obtained by examining the line at probit values 5 and 6.

Accordingly, Figs. 4 and 5 permit the estimation of shelf life by projecting the sigmoid tails upon a completely linear graph; the statistically imprecise tails are estimated by making their projections partly

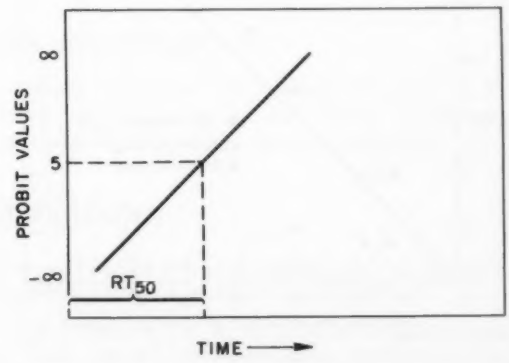

Fig. 5 Probit transformation of the lethality rate curve shown in Fig. 3.

dependent on the statistically precise midportions of the curve.

The relation between spoilage time and toxin-development time thus can be estimated most closely in terms of these calculated RT_{50} and TD_{50} averages.

Judgment of Inexpert and Expert Panelists. As mentioned earlier, certain consumers have peculiarities of odor or taste threshold that make them likely to eat spoiled food. These individuals constitute the population segment with the greatest risk of food poisoning. They would be as likely to accept spoiled nonirradiated food as they would be to consume spoiled irradiated food. To quantitatively estimate this population segment, the following procedure has been adopted.

The judgment of *each* member of an inexpert panel is compared with the *average* judgment of an expert panel. The number of days before the inexpert panelist rejects the sample because of spoilage is compared with the number of days before the expert panel *unanimously* rejects the sample; the times of rejection are plotted as shown in Figs. 6 and 7.

Figure 6 shows data for an inexpert panelist who, nevertheless, consistently agrees with the expert panel. Figure 7 shows data for an inexpert panelist who seldom agrees with the experts; because this panelist cannot detect spoilage as soon as the experts do, he represents the "population at risk." (In both figures, temperatures were not indicated because no temperature effect was found in the study.) The straight lines on the graphs are the lines that would be obtained if the judgment of the inexpert panelist agreed perfectly with that of the expert panelists. Points that fall above this line indicate that the individual was less sensitive to spoilage than the experts were; points that fall below indicate he was presumably more sensitive than they were.

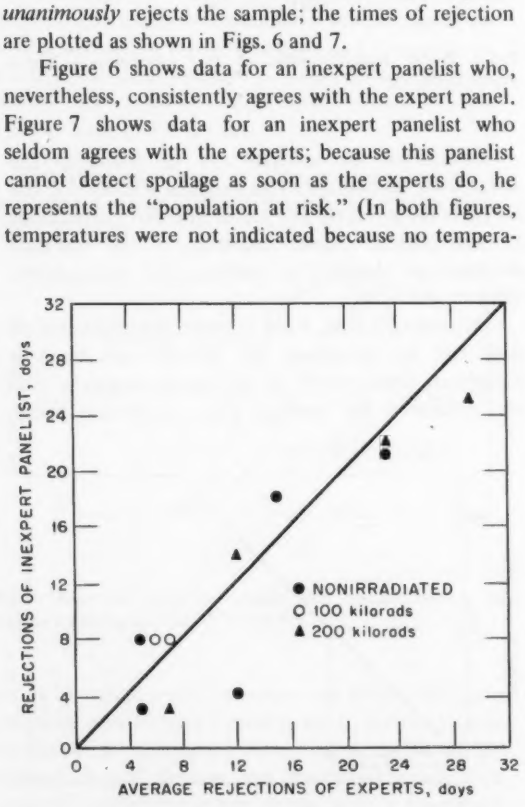

Fig. 6 Comparison of rejections by sensitive, inexpert panelist with the average rejections of an expert panel. Line indicates where perfect agreement would occur.

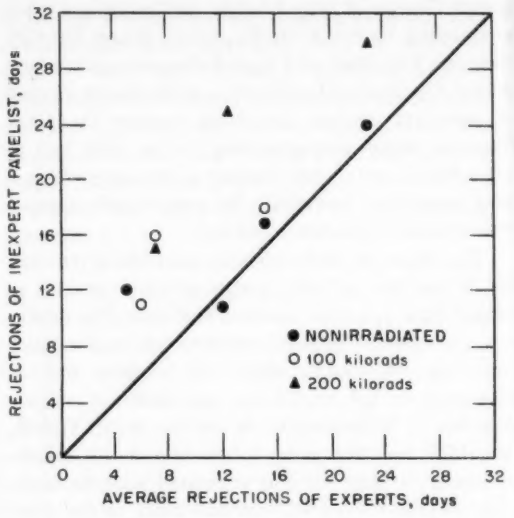

Fig. 7 Comparison of rejections of insensitive, inexpert panelist with the average rejections of an expert panel. Line indicates where perfect agreement would occur.

The consumers thus far studied in this way have shown no systematic shift in sensitivity—toward either greater sensitivity or less sensitivity—with level of irradiation, with temperature, or with storage time. That is, sensitivity—or lack of it—is independent of these variables. This finding simplifies the problem of identifying persons who lack sensitivity to the spoilage of food. The graphical representations (Figs. 6 and 7) may be quantified further by least-squares computations; exact information will then be gained on the following two aspects of judgment: (1) the extent to which the slope deviates from 1.0 (i.e., from perfect agreement) will provide a precise measurement of increased or decreased sensitivity of judgment for the particular inexpert panelist as compared with the sensitivity of the experts; (2) the magnitude to which the points are scattered will indicate how consistently the inexpert panelist makes his judgments, whether this judgment be equal to that of the experts, better than that of the experts, or worse than that of the experts.

The tools of probit analysis and regression analysis as outlined above satisfy the basic requirements for estimating the safety factor in radiopasteurization with regard to botulism and for identifying the consumer population at risk. Currently, investigations applying these quantitative methods are under way on a nationwide basis. In this way, factors of geography, climate, and lot variability will be considered, so that a reasoned decision as to whether or not a botulism hazard exists in the radiopasteurization of fish products can be finally reached.

SAFETY FACTORS

At least three safety factors are inherent in the test design.

First, there is the proposed safety factor of 1000 in the inoculum level over the estimated natural incidence, which, by the way, should be determined accurately. Second, there appears to be a safety factor inherent in determining the time of toxin development by the mouse-injection method because the concentration of toxin required to kill a human being may be considerably more than that required to kill a mouse. In a limited amount of work, especially some involving mice (weighing about 20 g) and guinea pigs (weighing about 200 g), a relation was found between tolerance to the toxin and body weight—i.e., about 10 times as much toxin was required to kill the guinea pigs as was required to kill the mice. If this relation were to hold true, then 1000 times as much toxin would be needed to kill even a child as is required to kill a mouse. In the opinion of Meyer and Eddie,[14] the amount of toxin that will kill a man may be a few hundred times that which kills a mouse. This discussion is not intended to criticize the mouse-injection method, but rather to call attention to the inherent safety factor in its use. Third, there is evidence that large inocula can carry preformed toxin with them,[15] but there is no way to evaluate what safety factor this contributes to the overall procedure.

Finally, another safety factor protects even the insensitive individual. Most fish products are given some form of heat-treatment in their preparation for consumption. Fortunately the toxin of *C. botulinum* Type E is heat labile.[16,17] So cooking tends to destroy any toxin that might be present.

SUMMARY

The economic savings promised by the use of low levels of ionizing radiation are threatened by the uncertainty as to whether or not this treatment is conducive to the development of botulinum Type E toxin. The basis for this concern stems from facts regarding the natural occurrence of *C. botulinum* Type E in the marine environment, the ability of this organism to grow at temperatures maintained in domestic refrigerators, the relatively high resistance of this organism to low-level radiation, and the localized sites of anaerobiosis which may occur in packaged fish.

An empirical test is proposed in which a statistical comparison of the shelf lives of irradiated and nonirradiated fish with the times required for toxin to develop in irradiated and nonirradiated fish permits the determination of whether or not a botulism hazard exists. The spoilage of fish is determined on the basis of odor by an inexpert panel of about 20 members. The toxin development is measured by the mouse-injection method of analysis using samples purposely inoculated with various concentrations of spores of *C. botulinum* Type E.

For the purpose of analysis, the sigmoidal plots of shelf life and toxin development data are converted to the probit analysis. This transformation, normally used in drug-response tests, establishes whether or not the data represent a normal distribution, which characterizes much of the conventional statistical approach to data analysis. Once normality is established, the probit values permit convenient and precise estimates of the 50% response values together with relevant standard deviations and associated confidence intervals.

By a comparison of the response data of an ordinary individual panelist with the data of expert panelists, the effect of various parameters on the response of ordinary panelists or consumers can be determined. Inherent safety factors in the test design are described. (FEM)

ACKNOWLEDGMENT

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Section IV

Isotopes and Radiation Technology

Process Radiation Development

A Report of a Symposium in Munich, 1969, on the

Utilization of Large Radiation Sources and Accelerators in Industrial Processing*

By C. K. Beswick and H. C. Yuan†

Supplementary Keywords: *conference; synthesis; plant scale; pilot-plant scale; source, beta; source, gamma; accelerator; dosimetry; radiolysis; polymerization; modification, material; grafting; modification, fiber; coating; cross-linking; additive; source preparation; industry, stone, clay, and glass; industry; industry, textile; industry, plastics; industry, chemical; industry, wood; industry, rubber; cobalt-60; strontium-90.*

Abstract: *A brief review of the symposium on the Utilization of Large Radiation Sources and Accelerators in Industrial Processing held in Munich, Federal Republic of Germany, Aug. 18–22, 1969, is presented. The main topics covered are chemical synthesis, polymerization and modification of polymers, dosimetry, and engineering.*

Recent advances in radiation chemistry and radiation processing have stimulated research and development programs in the chemical and plastics industries. Successful commercial processes for polymerization have been developed through the application of gamma or electron-beam irradiation to initiate chemical changes. Following two previous symposiums in Warsaw, 1959 (Ref. 1) and in Salzburg, 1963 (Ref. 2), the current symposium,[3] sponsored by the International Atomic Energy Agency, highlights recent activities in fundamental research, process development, engineering, and operations in the use of large radiation sources and accelerators. One hundred eighty-six participants from 29 countries and 5 international organizations attended the symposium. There were nine sessions for the presentation and discussion of 50 papers. The four main topics were: (1) chemical synthesis, (2) polymerization and modification of polymers, (3) dosimetry, and (4) engineering.

Particularly noticeable were extensive activities in polymerization and the modification of polymers; these activities included grafting, surface curing, textile treatment, composite material fabrication, and the vulcanization of elastomers. The trend in radiation processing is toward diversification to further exploit the technology. Nevertheless, the symposium included many papers that merged theory and practice.

CHEMICAL SYNTHESIS

Pilot Plants

Pilot plants for radiation-induced chemical processes were described. Both ^{60}Co and accelerators have been used as sources of radiation for initiating reactions in flow systems.

The use of an accelerator for the gas-phase synthesis of hydrogen chloride was reported by Konkov.[4]

Danno[5] described the chlorination of dichloroethane at the Takasaki Radiation Chemistry Research Establishment, Japan, using ^{60}Co sources arranged in two different configurations—inner-source and outer-source types. The effect of flow rates and dose rates on the product distribution of polychloroethanes has been studied and compared with the results of batch studies.

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†International Atomic Energy Agency, Vienna, Austria.

Rösinger[6] reported on the sulfoxidation of normal paraffins. The reaction rate was slow at low dose rates and was appreciably affected by the mass transfer rate of the gaseous reactants. The use of polychloromethanes and acetic anhydride to increase the rate of sulfoxidation was reported by Asinger and Saus.[7]

The performance of a tubular reactor and a continuous-flow stirred tank reactor has been analyzed at the Brookhaven National Laboratory.[8] Irradiation of aerated Fricke dosimeter solution showed the effect of absorbed dose on conversion. In large conversions the rate of radial mixing in the once-through tubular reactor and the degree of segregation in the stirred reactor caused deviations from either plug flow or complete mixing in the reaction system. These findings provide the basis for a rational approach to reactor design in radiation processes.

Radiation Chemistry

Swallow[9] reviewed the use of pulse-radiolysis techniques to study active species, including hydrated electrons, anion complexes of halogen atoms, excited states, and free radicals of aromatic compounds. Williams[10] discussed ion-recombination processes and the phenomenons of trapped electrons in the glassy state or crystalline structure.

The radiation-induced addition reactions involving the ethylenic double bond in chloroolefins and the reaction of 2-propanol with maleic acid were the other topics on chemical synthesis.

POLYMERIZATION AND MODIFICATION OF POLYMERS

The fundamentals of radiation-induced copolymerization were reviewed by Hummel,[11] who described copolymer systems containing ethylene, fluoroethylene, isobutene, and sulfur dioxide. Williams[10] discussed the role of free ions in ionic polymerization and the effect of extreme dryness in such a system.

Solid-State Polymerization

The solid-state polymerization of trioxane, which has entered the stage of pilot-plant studies, was reviewed by Hayashi,[12] who also discussed the topographic structures of polyoxymethylenes. Tabata and coworkers[13] illustrated the features of the nucleation process in the solid-state polymerization of itaconic esters. Through a measurement of the lifetime of positronium, they observed the effect of nucleation on the induction period of a typical solid-state polymerization reaction. Kiss[14] reported that the polymerization of acrylonitrile in the channel complex of urea was another example of solid-state polymerization leading to the formation of oriented crystalline polymers.

Graft Polymerization

Machi and Silverman[15] discussed the grafting of styrene to polyethylene and also to ethylene–propylene copolymer. Nonuniform viscosity of the amorphous region in polyethylene influenced the covalent grafting rate. The occlusion of homopolymers of styrene in the polyethylene matrix was studied by solvent extraction.

Seguchi and Tamura[16] conducted electron-spin-resonance studies of methyl methacrylate with polyethylene. Although both alkyl and allyl radicals initiated grafting reactions, the allyl radicals were more reactive.

Laizier and Wajs[17] reported on the improvement in hydrophilic properties and gas permeability of silicones, resulting from grafting with *N*-vinylpyrrolidone.

Modification of Textiles

In the radiation modification of textiles, Hoffman[18] explained the kinetics of grafting reactions and stressed the role of the diffusion of monomer molecules into the matrix of fibers. The current status of the technology for durable press was reviewed, and the improvement of wetting properties of synthetic fibers by grafting with hydrophilic monomers was discussed with respect to surface energy.

Blin et al.[19] reported the vapor-phase grafting of acrylic acid to polyester fibers for the improvement of hydrophilic properties.

Surface Curing

Electron-beam curing of surface coatings has become a commercial success very recently. Blin and Gaussens[20] reported the effect of dosage on the gel formation of unsaturated polyesters, acrylic esters, and epoxy acrylates. The effect of oxygen on the properties of cured films was also investigated.

The use of polyester–polyethylene film along with unsaturated polyesters for the surface treatment of fiberboard was reported by Miettinen,[21] and the economics of this process was compared with that of the peroxide-catalyzed process discussed by Rotkirch.[22]

Economics of aluminum or steel coil coating was the subject of Morganstern's paper,[23] which illustrated

the adaptability of electron-beam curing to high-speed production lines. A drastic reduction of operating cost is the merit of radiation curing, which could be of real significance if much higher line speeds (approximately 1000 ft/min) are considered.

Vulcanization of Elastomers

Balestic[24] reviewed the dose requirement in the cross-linking of natural and synthetic elastomers, with special emphasis on the vulcanization of elastomers based on polyfluoroethylenes.

The properties of the films obtained by radiation-induced vulcanization of natural rubber latex were discussed in a paper by Laizier et al.[25] Additives, including carbon tetrachloride, divinylbenzene, etc., were used to reduce the dosage requirement for the vulcanization of natural rubber and polychloroprene.

The effect of radiation on the cross-linking of elastomers with allyl, acrylic, and vinyl compounds has been extensively investigated by Balestic[26] and his group. The mechanical properties of such combinations were evaluated to test their applicability as binders for explosives.

Composite Materials Including Wood–Plastic Combinations

The impregnation of concrete with ~6% vinyl monomers followed by gamma irradiation is a current research program of Brookhaven National Laboratory. Manowitz[27] reported on recent developments and the results of corrosion tests relative to the handling of hot brine that may be encountered in water desalination plants. Monomers that can be cross-linked are particularly promising for this purpose.

A premixing technique followed by radiation curing was used by the Union Industrial Research Institute,[28] Republic of China, to make composites from red mud, sisal, and unsaturated polyester–styrene mixtures. Sufficient grafting of the polymer to the inorganic components was observed by X-ray-diffraction examination of the composites. The impact strength of the composites was correlated to the effect of process variables by means of response surface technology.

Laizier et al.[29] reported on impregnation systems containing a ternary mixture of monomer–solvent–water for the treatment of wood. By varying the composition of the system, it is possible to obtain different degrees of treatment. A comonomer system with vinyl carbazole was also found to be effective in modifying the cellular structure of wood. The grafting of polymer to wood was investigated by means of electron micrograph, hydrolysis, delignification, and histochemical methods.

Dalton[30] reported on the UKAEA's activities on the product applications of wood–plastics based on an acrylonitrile–styrene (60 : 40) mixture. The durability of these products was shown during their use in carton and pattern production. Research activities in India and Austria were reported by Jayaraman[31] and Proksch,[32] respectively.

Pilot Plants

Stahel and Stannett[33] used a recirculating-flow reactor to study the polymerization of vinyl monomer systems. The reaction zone was confined to a tubular section in the circulation loop, and, by varying flow rates in the system, the reactor can be used to study polymerization under conditions ranging from plug flow to complete mixing. They investigated ionic homogeneous polymerization of styrene and also of α-methylstyrene. Emulsion polymerization of styrene and vinyl chloride was also studied.[34]

Pilot-plant studies on the vulcanization of natural rubber latex were reported by Icre.[35] With an accelerator it has been possible to process 2 tons of latex per hour in a continuous-flow tubular reactor system.

DOSIMETRY

The distribution of flux during irradiation can influence localized rates of chemical changes as well as product uniformity. The current practice of dosimetry was reviewed and various methods were compared by Holm.[36] The effects of flow characteristics and degree of mixing in fluid systems were discussed by Hill and his coworkers.[8]

The importance of dose depth distributions in electron-beam irradiation has been shown in the cross-linking of polyethylene insulation used in cables and wires. The approach through the backscattering effect as revealed by Wiesner[37] was to circumvent and overcome the difficulties associated with dose-distribution problems. A theoretical analysis of electron beams from both line sources and plane-parallel sources was performed to correlate the angles of scattering, geometry, and structure of targets. Using Goudsmit and Sanderson's multiple scattering theory, Kniedler and Silverman[38] lumped successive collisions into one multiple collision and proposed four computer programs for the solution of boundary crossing and angular distribution of scattering problems.

On the measurement side, a radiochromic dye system incorporated into films, paper, or gels was described by McLaughlin and Hussmann.[39] After irradiation the dyes form stable excited-state molecules to sustain color stability. The image contrast and resolution of dye films were reproducible for dosimetric purposes over a wide range of electron and gamma-ray energies. Dvornik[40] reported the use of an ethanol–chlorobenzene dosimeter for electron-beam dose rates up to 10^9 rads/sec.

ENGINEERING

Only the papers referring to the design of radiation sources and accelerators are described here since pilot-plant and reactor-design development has been summarized under the chemical synthesis and polymerization sections.

Electron-accelerator design activities in the USSR were reported by Abramyan,[41] who summarized the various models—from the compact 0.5-MeV transportable assembly to machines of 1 to 3 MeV with a power output between 10 and 30 kW. A high-intensity proton accelerator of 4 to 5 MeV was also mentioned. In Konkov's[4] work the magnetic focusing principle has been used to concentrate the beam. These accelerators were used in the cross-linking of polyethylene, grain disinfestation, etc.

The fabrication of beta sources from strontium silicate beads for process irradiation was reported by Case,[42] of Oak Ridge National Laboratory, USA. This laboratory has designed thin-walled capsules that can provide approximately 30% of the energy emitted from ^{90}Sr.

Christen[43] described the design for housing a ^{60}Co source on roof shieldings to facilitate the transfer of source elements and also a stack conveying unit for the continuous handling of bulk materials.

MISCELLANEOUS

Pastuska[44] described the radiation-induced reduction of a chromium salt from the hexavalent to the trivalent state in the presence of glutaraldehyde in the tanning of hides.

Cramer et al.[45] reported improvement in wet strength of paper by grafting. Compton et al.[46] investigated the effect of radiation on the oxidation, settling rate, and sedimentation of solids in waste waters and sewage sludge.

Silverman[47] summarized the general aspect of this symposium. (REG)

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Radiation Processing of Poultry Wastes

By W. M. Jackson*

Supplementary Keywords: *pollution; source, gamma; agriculture; facility description; cobalt-60.*
Abstract: *A system containing a 50-thousand-Ci ^{60}Co source for radiation processing of poultry litter is described.*

The outstanding success of the U. S. poultry industry in producing highly efficient farms for the production of meat and eggs in enormous quantities has resulted in some areas having serious waste-handling problems. The problem of disposing of poultry wastes is further accentuated by the tendency of the industry to concentrate in localized areas, such as Sullivan County, N. Y., and the Atlanta, Ga., area. Because of the increasing pollution from poultry wastes, the federal government has awarded Cornell University a grant to study the problem.

The inefficiency of poultry in utilizing the nutrients in feed has long been recognized, and numerous studies have been carried out to evaluate the reuse of poultry wastes (litter) in feeding studies for poultry, swine, sheep, and cattle.[1–5] The performance of animals fed poultry wastes with various bases has generally been good, and, in some cases, superior to

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that of control animals, indicating that considerable feed value was derived from the material. Treatment of the litter used in these studies varied from none to, at most, thermal drying. In most of these studies, roughage and other feed materials were added in various amounts. The major finding was that, as the poultry-waste content of the feed increased, the palatability and intake decreased. Other problems mentioned by these investigators were dustiness of dry litter, unpalatability of wet litter, the presence of such foreign objects as metal, and the possibility of chemical residues and disease organisms.

provision for removal of the solids from the inner walls of the irradiator, which could decrease the radiation dose to the liquid and impede flow.

The first system using this irradiator is on order by Agritomics, Inc., Washington, D. C., for treatment of poultry wastes (Fig. 1). The radiation source is 50 thousand Ci of ^{60}Co, and the system is designed for a capacity of 60 tons of aqueous slurry per day containing 17 to 18% solids. The slurry will receive a radiation dose of 120 thousand rads, which is sufficient to kill most of the bacteria and will enhance rapid separation of the solids. This dosage is about 15 times

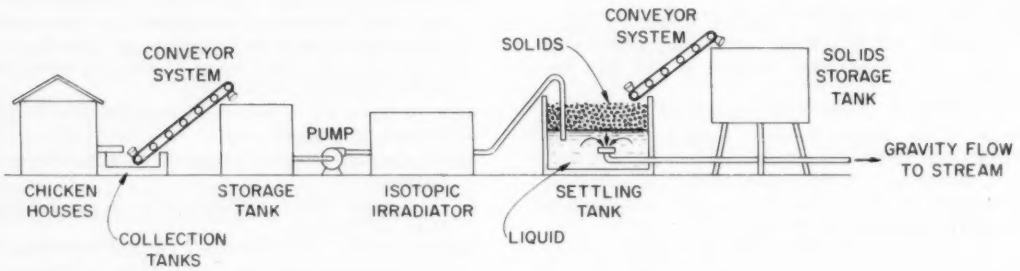

Fig. 1 Poultry-waste-treatment system using radioisotopic irradiator.

These findings suggested that many of the problems might be eliminated if radiation treatment of the poultry wastes could be combined with a limitation of the amount of waste in the reconstituted feed. Research on irradiation of sewage sponsored by the USAEC and other organizations has shown that irradiation increases sedimentation, enhances oxidation of chemicals, destroys bacteria, and eliminates odors.[6-12] The Sanitary District of Greater Chicago has incorporated these findings into a design study of an irradiation facility for processing about 2 million gal of sewage sludge per day. The use of about 4 million Ci of ^{60}Co or a corresponding amount of ^{137}Cs should decrease the cost[13] of sludge disposal from $57 to about $16 per ton.

American Nuclear Corporation, Oak Ridge, Tenn., has developed[14] an irradiator for sewage and animal wastes which is almost 100% efficient in utilization of the gamma energy from ^{60}Co or ^{137}Cs. The flow-through design uses several passes by the centrally located sources to ensure uniform dosage to the liquid, with the total dose to the liquid being determined by the activity of the sources and the flow rate through the irradiator. A unique feature of the design is the as great as that planned by the city of Chicago for treating sewage sludge. Adequate provision has been made for adjusting the flow rate to obtain the desired level of pasteurization and for compensation as the ^{60}Co decays. (MG)

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Section V

Isotopes and Radiation Technology

Applications in Life Sciences

^{133}Xe Pulmonary-Function Analyzer

By A. S. Blum*

Supplementary Keywords: *medicine; diagnosis; tracer; ventilation; xenon-133.*

Abstract: *A mobile system is described for the automatic, separate measurement of the function of each lung. External measurement of the gamma radiation of ^{133}Xe eliminates the need to seal catheters within the bronchial tree. Lung-volume data are computed and displayed digitally in liters. A volumetric maneuver that calibrates the entire system, including the patient, makes this computation possible. The radioactive gas, supplied in a tank of compressed air, is metered and dispensed by an electrically operated valve. Radioactivity in exhaled air is removed by a trap; this minimizes the problem of handling radioactivity and avoids environmental contamination.*

The hope of arresting many lung diseases, such as emphysema and bronchogenic carcinoma, rests upon the ability to detect lung pathology before so much function is lost that the disease is clinically manifest. In a study of 2000 subjects, Hutchinson[1] found that spirometric measurement of vital capacity could be predicted on the basis of height and age. A reduction of this volume below predicted levels accompanied, and often preceded, clinical manifestation of lung disease. His work was published in 1846, but a reduction in spirometric ventilation values below predicted levels is still recognized as a sensitive indicator of lung pathology.

If the function of each lung is measured separately, even greater sensitivity is achieved, by virtue of data asymmetry, before the sum of the two lungs deviates significantly from predicted values.

There is another vital requirement for quantitative pulmonary-function data from each lung. When a surgeon is contemplating removal of a lung, or a portion thereof, he must know if there will be enough function in the remaining lung tissue to support life.

PULMONARY-FUNCTION ANALYSIS

The total volume of gas in the lungs at full inspiration is the total lung capacity (*TLC*), which cannot be measured directly. The maximum amount of gas that can be moved from full inspiration to full expiration is the vital capacity (*VC*), which is easily measured by a spirometer. The amount of gas remaining in the lungs at full expiration is the residual volume (*RV*), which cannot be measured directly; gas-dilution techniques and a gas analyzer are required. The sum of *VC* and *RV* equals *TLC*. One of the most useful indicators of airway obstruction is the forced expiratory volume in 1 sec (FEV_1), the volume of gas that can be exhaled in 1 sec from full inspiration with maximum effort. This is measured by connecting a spirometer to the patient's mouthpiece and recording the sum of the ventilation of both lungs.

To get these data for each lung separately requires bronchospirometry. With the patient under local anesthesia, a four-lumen catheter is inserted into the trachea. One branch is sealed in the left main bronchus with an inflated cuff; another branch is sealed in the trachea and receives gas from the right lung. Gas from each lung flows to a separate spirometer and gas analyzer. Because of the small catheter lumens, no information on flow rate (*FEV*) can be obtained; and, because of the stress to the patient, meaningful capacity values in liters are not obtained. Instead, relative volume on each side is multiplied by total volumes found by previously performed conventional spirometry. Although bronchospirometry was introduced[2] in the 1930s, very few centers perform the procedure, even for preoperative evaluation.

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RADIOACTIVE-GAS TECHNIQUE

Knipping and associates[3] first used radioactive gas to study pulmonary function at the University Clinic in Cologne in 1953. Multiple collimated detectors were placed against the chest to record the varying amounts of radiation in different regions of the lungs as the gas was inhaled and exhaled. Investigators in Montreal,[4] London,[5] and Malmö[6] expanded on these ventilation techniques and introduced perfusion measurements as well.

When the relatively insoluble gas is injected intravenously, it is released in the first gas space it reaches. The amount of radioactivity in a lung region is then directly proportional to the pulmonary perfusion of that region.

All the published techniques convert detector impulses into analog signals with rate meters. A signal is recorded and subsequently converted to digital form for computation. These studies have resulted in a much greater understanding of man's pulmonary physiology in both normal and disease states. However, the equipment is cumbersome, the data processing is laborious, and the results are in relative terms, not in liters, because externally measured radiation levels cannot be converted to gas volumes. An excellent review of the subject is presented by Miörner[6] along with the most practical clinical technique for relative regional-ventilation perfusion measurements.

These measurements can be made simultaneously, safely, and automatically by a new pulmonary-function analyzer using the gamma-emitting inert-gas isotope ^{133}Xe. No catheters are used, only a mouthpiece and noseclip. Values for each lung's *VC* and *RV* in liters, as well as for each lung's FEV_1 in percent of each lung's total capacity, can be displayed in digital form without any calculations by the operator. After an intravenous injection of the gas in solution, the fraction of the total pulmonary blood supply perfusing a lung can also be displayed.

The new ^{133}Xe technique has different objectives: (1) quantitative volumetric data in liters for each lung separately, (2) data presentation in readily interpretable format (classical spirometric values) for comparison with predicted norms, and (3) simplicity of gas handling with automatic computation.

DESCRIPTION OF THE INSTRUMENT

The ^{133}Xe pulmonary-function analyzer is a completely self-contained system (Fig. 1) for the automatic collection and display of information on the ventilation and perfusion of each lung. The subject is seated (Fig. 2) with his back against a double box, his spine along a central partition. The mouthpiece and valve are suspended in front of the patient. They connect by hoses to a tank of a ^{133}Xe–compressed-air mixture and an exhaust trap (Fig. 3). On one side of the unit are strip-chart recorders for analog display of the counting rates over each lung. A selector switch and "start count" push button are the only operating controls. Numerical data are calculated automatically and displayed by the usual Nixie tubes.

In keeping with the dictum *primum non nocere,** a special mouthpiece has been designed so that the portion of the mouthpiece where incoming air mixes with exhaled air can be replaced after use by the patient to eliminate the danger of cross contamination between patients. This problem has too often been ignored in the design of pulmonary-function apparatus.

The inert gas ^{133}Xe is either injected intravenously in saline solution for perfusion studies or inhaled in an air mixture from a pressurized tank for ventilation studies. Activated charcoal at −70°C adsorbs xenon from exhaled air.

A NaI crystal scintillation detector, centered over each lung, measures radiation from the xenon gas in that lung. The crystals are located at the back of the double box, one on each side of the central vertical partition. The walls and the central vertical partition are lead lined; thus each crystal is at the rear of an elongate lead chamber, which is closed at the open end by a single lung. The detector is far enough from the chest (18 in.) that sensitivity is relatively uniform from apex to base and front to back. The lead partition and the spine effectively separate the radiation from the two lungs. The amount of cross talk was tested in a patient whose right lung had been removed (Fig. 4). Essentially all the volume measured was in the remaining lung.

The impulses from the two detectors pass through pulse-height analyzers tuned to the 81-keV gamma-energy peak to reduce scatter and background. The selected pulses then pass into rate meters whose outputs go to a two-channel strip-chart recorder, which provides analog recordings of radiation intensity vs. time as gas goes into and out of each lung. However, the use of rate meters causes information loss. The impulses are simultaneously fed to a digital processing unit that integrates the pulses received over fixed time intervals for optimum counting statistics and performs the discrete mathematical operations indicated by the

*"First of all, do no harm."—*The Editor.*

Fig. 1 Schematic of the ^{133}Xe pulmonary-function analyzer. (U. S. and foreign patents applied for.)

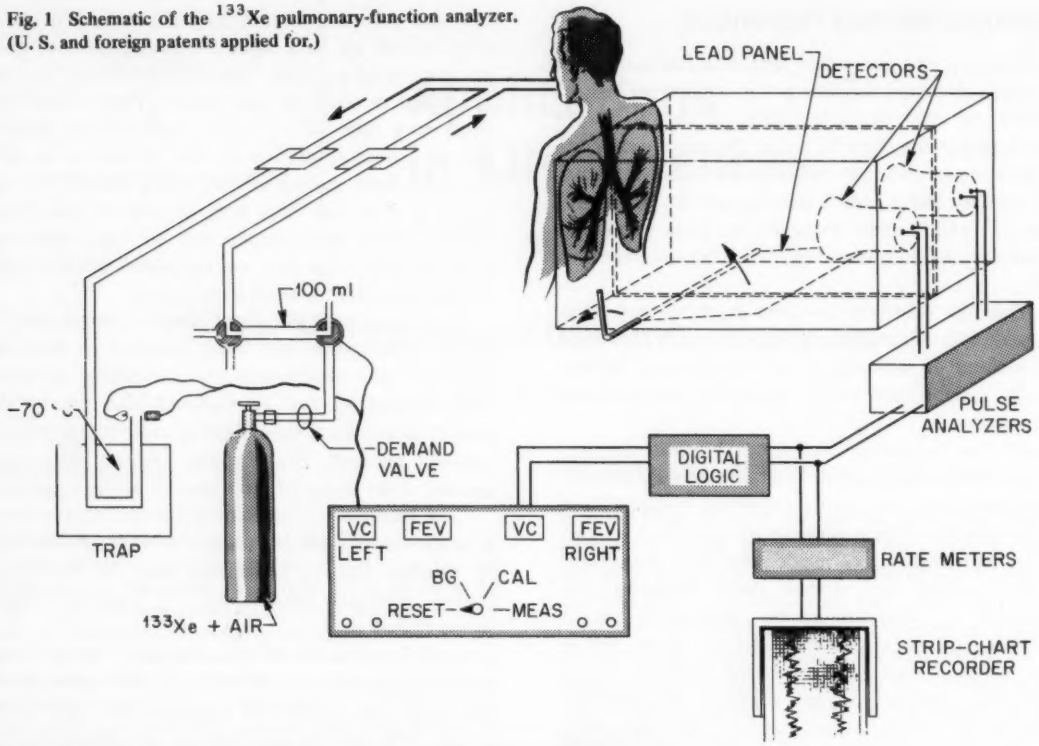

Fig. 2 Test subject with back to detectors and nursé holding mouthpiece of pulmonary-function analyzer. Digital output can be seen on lower right section of analyzer.

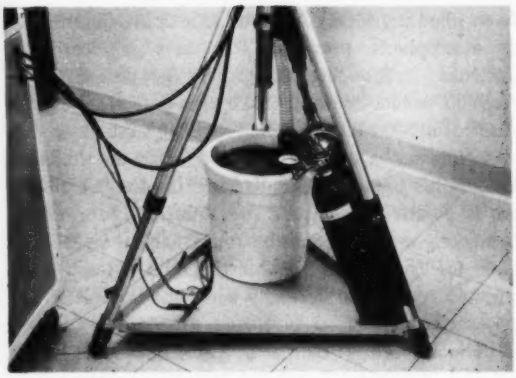

Fig. 3 Gas-handling system and ^{133}Xe trap for pulmonary-function analyzer.

multiposition selector switch. In contrast to the graphic analog data, these data are precise. The results of the automatic computations appear as numbers on the control panel.

Results displayed are

Vital capacity of left lung in liters.
Vital capacity of right lung in liters.
(FEV_1 of left lung)/total left lung capacity.
(FEV_1 of right lung)/total right lung capacity.
Residual volume of left lung in liters.*
Residual volume of right lung in liters.*

*The instrument now in operation does not include the digital logic to compute these terms automatically. They are calculated manually from the chart and the VC, since calibration in liters is derived from VC in the equation for RV. (ASB)

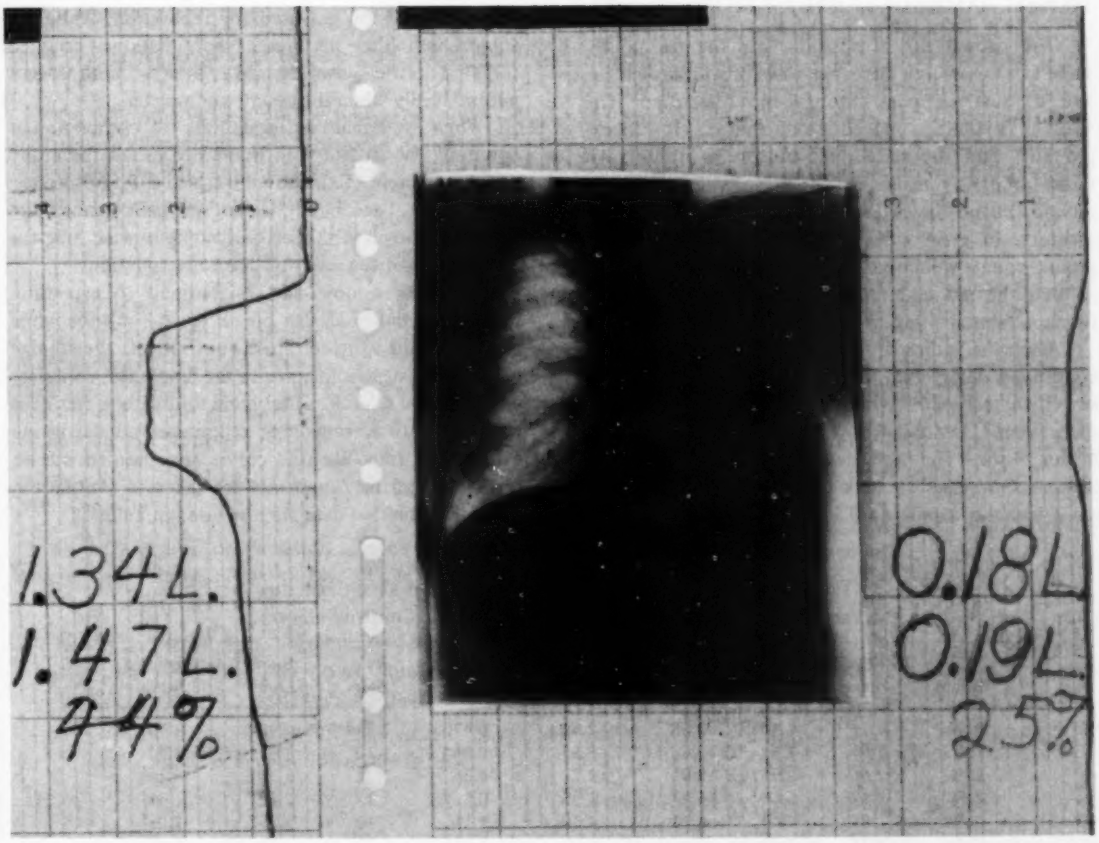

Fig. 4 Duplicate readings of vital capacity in a patient with right lung removed. Essentially all the ventilation is seen to be on the unoperated side, showing how well the instrument separates data from each lung.

System Calibration

To convert radiation intensity (counts per unit time) to liters of gas, the system (which includes the patient's chest) is calibrated by introducing, first, a known volume (0.1 liter) of the gas mixture into the subject's lungs and then room air to full inspiration. While the subject is holding his breath, the sum of counts from both detectors is stored during a 4-sec counting interval. The sum of xenon activity will be equivalent to 0.1 liter; the fraction in each lung need not be known if detector sensitivities are equal. The instrument now has inscribed in its memory the information of the counting rate of 0.1 liter of that gas mixture in that chest. From this information, absolute volumes in liters can be derived from counting rates while various ventilation maneuvers are performed.

VENTILATION DETERMINATION

The patient sits in position with the gas mouthpiece and noseclip in place; the valve provides room air, and exhaust air goes through the filter trap. The selector switch is moved from "reset" to "background," and the start-count button is pressed. An indicator light remains on for 4 sec while the background count from each detector is stored in a memory. In every subsequent operation these background counts will be subtracted from the total counts, so that the net counts used in the calculations will represent xenon entering the system.

After the indicator light signals that background counting is completed, the operator moves the selector switch to "calibrate" while the patient is exhaling; and the patient is instructed to take a full breath and hold it for 4 sec. The automatic valve connecting the xenon–compressed-air tank to the inlet of the mouthpiece includes a pipe of 0.1 liter capacity, which has been filled previously with the radioactive gas mixture at atmospheric pressure. The valve is electrically switched, introducing the gas in the pipe into the fresh-air stream being inhaled by the patient. The gas is flushed into the lungs by the following fresh air so that none remains in trachea or mouth. While the subject is holding his breath, the radiation from the 0.1 liter of gas is counted for 4 sec. The counting is started by depressing the start-count button. When the signal light indicates completion of counting, the patient is instructed to breathe normally while the calibration gas is washed out.

The operation switch is turned to the fourth position, "measure," and the patient is instructed to exhale completely, take a full breath, and hold for 4 sec. The automatic valve connects the mouthpiece to the xenon–air mixture at atmospheric pressure so that the entire inspiratory vital capacity is filled with the same composition gas used for calibration. While the subject is holding his breath, the radiation is counted for 4 sec. The valve disconnects the xenon source automatically when the count is completed.

When the signal light again indicates completion of counting, the patient is instructed to exhale forcefully and completely. Exhalation triggers a 0.5-sec timer, and then a 1-sec count is automatically made. The measurement gives the gas remaining in each lung for an average of 1 sec after the start of exhalation.

The patient now inhales fresh air to maximum inspiration and holds his breath again for 4 sec while another count is made. This count reflects the volume of radioactive gas remaining in the lungs after complete exhalation, i.e., RV. The patient breathes fresh air normally until all remaining xenon accumulates in the exhaust-line trap. Washout curves are recorded, but no further digital measurements are taken of ventilation. Typical ventilation data are presented in Table 1.

Table 1 Comparison of Measured and Predicted Vital Capacities and Residual Volumes for Nine Asymptomatic Control Subjects

Patient	VC_L, liters	VC_R, liters	Sum, liters	Predicted, liters	RV_L, liters	RV_R, liters	Sum, Liters	Predicted, liters
P. W.	1.18	1.50	2.68	2.70	0.472	0.947	1.42	1.70
P. B.	1.77	1.91	3.68	3.55	0.664	1.10	1.76	1.51
L. K.	2.66	2.95	5.61	4.22	1.38	2.21	3.59	2.14
P. M.	2.47	2.50	4.97	4.36	0.967	1.25	2.22	1.85
L. W.	1.84	2.40	4.24	4.10	1.16	2.10	3.26	2.03
D. B.	2.31	2.14	4.45	4.07	0.735	1.07	1.80	2.06
E. N.	1.48	1.76	3.24	3.68	1.18	1.41	2.59	2.98
R. E.	1.89	2.89	4.78	4.65	0.576	1.17	1.75	1.97
J. P.	1.68	1.59	3.27	4.36	1.05	1.59	2.64	2.13

PERFUSION DETERMINATION

Perfusion measurements are made after an intravenous injection of xenon gas in a saline solution. An estimated 95% of the dissolved gas is released to the air space in a single passage through the pulmonary alveolus. Since most of the gas is lost before blood reaches the left ventricle, gas spaces perfused by the bronchial circulation will not contain xenon, and xenon in each lung will be proportional to perfusion by the pulmonary circulation alone.

The pulmonary perfusion of each lung may be measured at any stage of the respiratory cycle, but the counting interval should not be started until the rate-meter curves show that the injection bolus has passed through the heart. A single 4-sec counting interval is used without calibration since only fractional perfusion on each side is determined.

DERIVATION OF EQUATIONS

The following values, representing counts collected in fixed time intervals, may be stored electronically within the data-processing unit:

A = full-vital-capacity breath.

B = background.

C = calibration.

D = count after 1 sec.

E = residue after complete exhalation.

P = count after injection.

Subscripts L and R denote left and right, respectively, of chamber (i.e., lungs).

Vital Capacity

$C_L + C_R$ = sum of radiation counts from both lungs after 0.1 liter of gas mixture has been inhaled.

$C_L + C_R - B_L - B_R$ = net counts due to 0.1 liter of gas in lungs after subtracting for background.

$A - B$ = net counts due to full vital capacity of gas, at same concentration as the 0.1 liter.

Then

$$VC = A - B \tag{1}$$

and

$$0.1 \text{ liter} = C_L + C_R - B_L - B_R \tag{2}$$

Dividing Eq. 1 by Eq. 2 and solving for VC gives

$$VC = 0.1 \frac{A - B}{C_L + C_R - B_L - B_R} \tag{3}$$

These values are all measured separately; therefore

$$VC_L = 0.1 \frac{A_L - B_L}{C_L + C_R - B_L - B_R} \tag{4}$$

and

$$VC_R = 0.1 \frac{A_R - B_R}{C_L + C_R - B_L - B_R} \tag{5}$$

Residual Volume

The gas is assumed to be mixed in the entire lung capacity after breathholding at full inspiration; data obtained with helium indicate this is true. The net count after inhalation of full vital capacity was $A - B$. After mixing with the total lung capacity, the radioactivity is present in the same amount but diluted by the residual volume. Therefore $A - B$ represents total lung capacity. When a vital capacity is exhaled, the net count remaining, $E - B$, is proportional to the residual volume; and the difference, $A - B - (E - B)$, is proportional to VC.

$$RV = E - B \tag{6}$$

$$VC = A - B - (E - B) = A - E \tag{7}$$

Dividing Eq. 6 by Eq. 7 and solving for RV,

$$RV = \frac{VC\,(E - B)}{A - E} \tag{8}$$

Since VC is in liters in Eq. 3, RV is in liters. Adding the specific notation for each lung,

$$RV_L = \frac{VC_L(E_L - B_L)}{A_L - E_L} \tag{9}$$

and

$$RV_R = \frac{VC_R(E_R - B_R)}{A_R - E_R} \tag{10}$$

Forced-Expiratory-Volume Ratio

If forced expiration could be interrupted after 1 sec and the chest counted for 4 sec, the net count, $D - B$, representing gas remaining in lung after 1 sec would be obtained. The ratio $(D - B)/(A - B)$ would

be the fraction of the total lung capacity remaining, and $[1 - (D - B)/(A - B)]$ would be the fraction of the total lung capacity expired in 1 sec, i.e., FEV_1/TLC. However, the chest is counted for only 1 sec, and the result is multiplied by 4:

$$\frac{FEV_1}{TLC} = 1 - \frac{4D - B}{A - B} \tag{11}$$

Because expiration cannot easily be arrested at 1 sec while counting, the actual count is made around the 1-sec mark, i.e., from 0.5 to 1.5 sec after start of expiration. The results will deviate from the true 1-sec value to the extent that the rate deviates from a straight line during this period. For the separate lungs, the equation becomes

$$\frac{(FEV_1)_L}{(TLC)_L} = 1 - \frac{4D_L - B_L}{A_L - B_L} \tag{12}$$

and

$$\frac{(FEV_1)_R}{(TLC)_R} = 1 - \frac{4D_R - B_R}{A_R - B_R} \tag{13}$$

Perfusion

The equations for perfusion ratio in both lungs are similarly derived:

$$\frac{\text{Perfusion}_L}{\text{Total perfusion}} = \frac{P_L - B_L}{P_L + P_R - B_L - B_R} \tag{14}$$

and

$$\frac{\text{Perfusion}_R}{\text{Total perfusion}} = \frac{P_R - B_R}{P_L + P_R - B_L - B_R} \tag{15}$$

STATISTICS

The radiation emitted by a radionuclide obeys the laws of a true random phenomenon. Therefore the standard deviation of a measurement equals the square root of the number of counts measured. The greater the number of counts collected, the greater the precision.

In all the reported studies with xenon, pulses were fed to a rate meter for conversion to analog form; the varying voltage output was then fed to strip-chart recorders or magnetic-tape records or both; and the stored data in analog form had to be read out and converted back to digital form before calculations could be made. In such procedures, information is lost at each step, and each step adds to the cost and time of the operation. If all the counts received during the measurement interval are added in a scaler, the maximum available information can be obtained, and the calculations can be started directly with digital data.

The precision of measurement can be improved by increasing the sensitivity of the detectors, the time intervals, or the amount of ^{133}Xe used. The calibration volume of 0.1 liter is only 2% of the volume of gas used to determine vital capacity. This is the limiting point statistically. The calibration affects only the absolute values; it has no influence on measurement of symmetry. The calibration volume could easily be increased to 1 liter in normal adults either to give greater precision or to lower radiation doses by a factor of 10. The small volume was chosen so that the test could be used in children and patients with severe lung disease and also could be introduced at any point of the respiratory cycle. There is evidence that the first bolus of air entering from functional residual capacity (*FRC*) does not go to the bases of the lungs. Taking the calibration volume at close to tidal levels will probably give more valid results, especially in patients with severe lung disease; however, taking the calibration bolus at various levels of the respiratory cycle opens the way to more detailed study of pulmonary pathology.

Detector sensitivity can be increased by the use of large-cross-section scintillation crystals. Large-diameter general-purpose scintillation detectors are quite expensive because the crystal must be thick enough (5 cm) to absorb high-energy radiation. An instrument designed for the low energy of xenon can use a crystal less than 1 cm thick, and large-diameter detectors are then economically feasible.

RADIATION EXPOSURE

Lassen[7] estimated the radiation exposure to ^{133}Xe, from either the inhalation of 1 mCi/liter for 1 min or the intravenous injection of 5 mCi, to be: tracheal mucosa, 96.8 mrads; lung, 17.5 mrads; and gonads, 1.1 mrads. To use his exposure data requires a conversion factor. In this work a maximum concentration of 0.33 mCi/liter with an estimated 6 sec of breathing (4 sec of breathholding) gives a conversion factor of

$$\frac{6 \text{ sec}}{60 \text{ sec}} \times \frac{0.33 \text{ mCi/liter}}{1 \text{ mCi/liter}} = 0.033$$

Therefore the ^{133}Xe pulmonary-function analyzer gives doses of 3.2 mrads to tracheal mucosa, 0.58 mrad

to lung, and 0.036 mrad to gonads. In the perfusion studies, a dose of 0.05 mCi is adequate; 0.05 mCi/5 mCi = 0.01. Therefore the perfusion studies result in doses of 0.968 mrad to tracheal mucosa, 0.17 mrad to lung, and 0.011 mrad to gonads.

According to the International Commission on Radiological Protection (ICRP), the highest dose allowed for personnel in radiological work for most organs is 300 mrads each week of their working lives. The usual dose for a diagnostic chest X ray given in a medical facility is 26 mrads to the lungs. The dose from an X-ray machine of the mobile-van survey type is 220 mrads to the lungs. Therefore the ^{133}Xe pulmonary-function analyzer is a very-low-dose diagnostic device.

GAS-HANDLING SYSTEM

One of the obstacles to widespread application of xenon in clinical diagnosis is the same property which makes it so valuable. No matter by what route it is administered, the gas is exhaled to the air within minutes. As long as the room air is rapidly replaced, there are no hazards to personnel or to the accuracy of measurement. Large air-collecting bags or hoods exhausting outside the building are most often used. These limit the convenience and mobility of the procedures.

With the pulmonary-function analyzer, xenon for ventilation is automatically kept within the closed system. The gas has a biological half-life of ~1 min, although its physical half-life is 5.27 days. It emits a 0.345-MeV beta ray and 0.081- and 0.031-MeV gamma and X rays. The gas is provided in a small cylinder containing 150 liters of air and less than 0.1 ml (50 mCi) of ^{133}Xe compressed to 2000 psi. The fittings and demand valve are commercial scuba gear. No tools are required to connect the tank to the system. The apparatus has a sufficient range of sensitivity that a tank may be used for at least 2 weeks with acceptable statistical accuracy.

The demand valve feeds gas at atmospheric pressure to the system. The negative pressure required to open the valve is so slight that it does not affect the normal subject's vital capacity as compared to conventional spirometry (Fig. 5). This statement is not true for emphysema patients; the sum of their differential vital capacities is much less than that found by spirometry (Fig. 6). For these cases a bag reservoir, provided in the gas inlet line, can be filled in advance. The bag is not used for screening tests, and the tests are therefore sensitive to pathology although not registering a true vital capacity. When pathology is detected, the test can be repeated with the filled bag to find the true vital capacity.

Xenon in saline for perfusion is dispensed from a sealed cartridge directly into a syringe for injection. Exact dose is not critical, since only relative perfusion on each side is measured.

Xenon Trap

A specially designed xenon trap incorporated into the apparatus passes all the patient's exhaled air but removes and retains all the xenon in a shielded container. Since this is a closed system, it may be used anywhere, even at bedside, without fear of contamination.

The trap consists of a set of baffles that conduct the exhaled air through two absorbers and two adsorbers in series:

1. Indicating soda-lime granules (sodium hydroxide, calcium oxide) absorb CO_2. At Dry Ice temperature, water is also removed.
2. Two activated-charcoal filters adsorb xenon at $-70°C$.
3. Soda-lime granules, which perform no active function, protect the charcoal from CO_2, which might back-diffuse into the trap from the exit and saturate the charcoal, exhausting its adsorptive potential for xenon.

Low temperature is maintained by Dry Ice or mechanical refrigeration. Absorption of CO_2 by soda lime is an irreversible reaction. Saturation is indicated by a color change visible through the transparent trap. Adsorption of xenon by activated charcoal at low temperature is a reversible phenomenon, and xenon may be desorbed by warming the filters to room temperature. The entrance and exit of the filter trap are at the top and, even if the trap is warmed, the heavy xenon (4.5 times as heavy as air) tends to remain in the trap in the absence of a current of air. Unidirectional valves at entrance and exit prevent inhalation of exhaled air. Since these valves have rubber flaps that seal off the air passages, the trap is closed when not in use. It would always be cold when in use.

The xenon can be pulled from the warmed trap and reused or discarded. However, the isotope decays so rapidly and is so easily shielded that the trap need not be emptied. The trap holds 1 lb of charcoal, which has an enormous capacity—more than 1000 Ci. At 0.001 Ci/test, there is no problem of saturation of the charcoal with xenon. The large amounts of CO_2 and

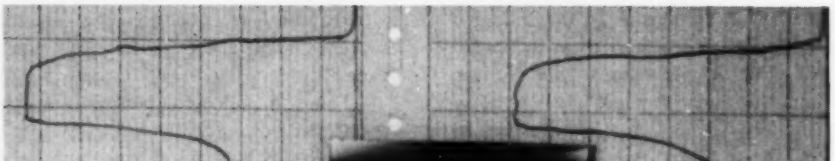

Fig. 5 Result of ventilation study of a normal individual. Digital and analog data are given on each side of the chest X ray. Upper figure is *VC*, and lower figure is FEV_1; FEV_1 is given as percent of *VC*. Conventional spirometry data are shown below the X ray; *VC* in liters is followed by percent predicted in parentheses.

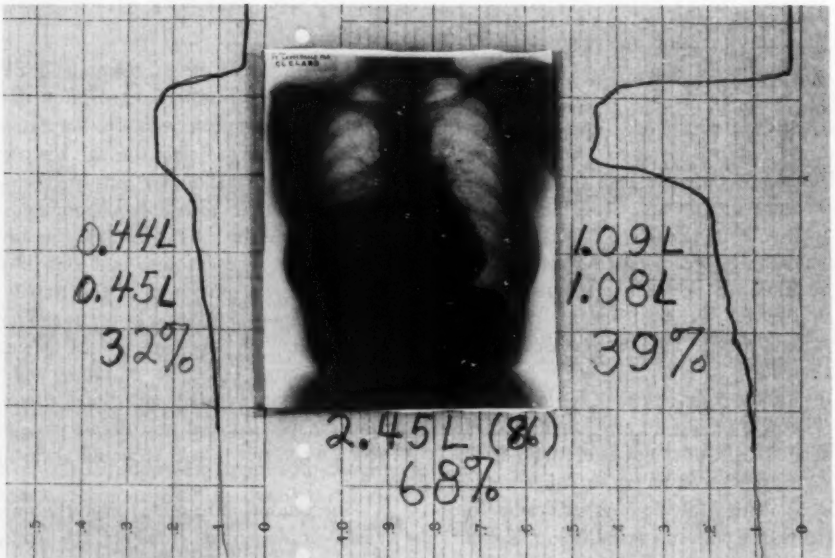

Fig. 6 Sensitivity of the ^{133}Xe analyzer. Patient had two-thirds of his right lung removed. Conventional spirometry indicated *VC* was 86% of the predicted value; pulmonary-function analyzer correctly shows that only one-third as much function remains in the right lung.

water in the breath could easily saturate the charcoal if it were not for the preliminary passage through the soda lime.

Safety Test

A 1.5-liter syringe was filled with the gas mixture and counted. A charcoal trap with a single valve was purged with the gas mixture. The same syringe was filled at a rate equal to an *FEV* maneuver (1 sec) with the gas after it had passed through the trap; 99.7% of the activity remained in the trap. The trap was kept at room temperature for 5 days; approximately 20% of the activity was lost when compared to a sealed standard of ^{133}Xe. The trap was moved each day, and the exit valve had been removed to allow diffusion.

REGIONAL FUNCTION TECHNIQUE

Lead panels may be interposed between patient and detector to shield the bases of the lungs. The panels in the current instrument (Fig. 1) are operated like a furnace damper. When the lever is raised, the lead panels shield the lower halves of the fields of view.

As soon as the 4-sec count interval is completed and while the subject is still holding his breath, the lever can be raised and lowered. Then the patient can exhale for the FEV_1 maneuver in the conventional manner. The recorder curves (Fig. 7), which up to this time have been indicating *VC* level, dip momentarily to lower levels indicating the fraction of gas in the upper halves. This technique can be repeated after exhalation so as to indicate the relative distribution of residual gas. These extra manipulations do not interfere with the quantitative data collection and offer a simple technique for localizing pathology to upper or lower lung.

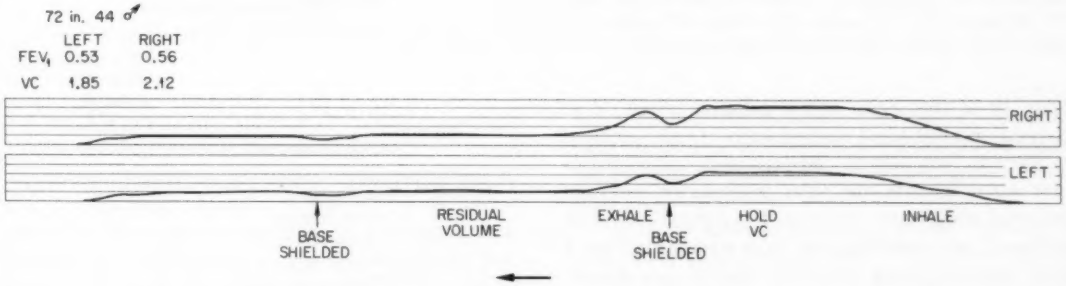

Fig. 7 Recorder curves showing use of regional function technique (lead shield over base of lungs).

SUMMARY

The ^{133}Xe pulmonary-function analyzer is a self-contained system that provides digital output of lung-volume data in liters. It incorporates several outstanding design features not available in other lung-function analyzers. One of these features is the digital output, and another is the trapping system that makes the system so safe. Digital Products Corp., Fort Lauderdale, Fla., is now manufacturing and retailing the complete system. This company also made the digital data-processing unit for the prototype system. (FEM)

ACKNOWLEDGMENTS

The author thanks Dr. W. S. Williams for the clinical material, as well as for his advice and encouragement, and L. Kelman of Digital Products Corp. for his major contribution to the design of the data-processing and control circuitry. This research was supported in part by the Friedman Fund.

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Survey of the Use of Radionuclides in Medicine—Phase II*

Summarized by Martha Gerrard

Supplementary Keywords: *diagnosis; tracer; data compilation; phosphorus-32; chromium-51; cobalt-57; cobalt-60; strontium-85; strontium-87m; technetium-99m; iodine-125; iodine-131; mercury-197; mercury-203; gold-198; survey, technical.*

Phase I† of this study was a national survey of all licensed and registered medical users of radionuclides. In Phase II, methods of diagnosis using radioisotopes were surveyed with particular emphasis on measures that minimize patient exposure. The persons contacted in Phase II were selected from those who in the Phase I study reported having carried out one or more of some 23 radiopharmaceutical procedures in 1966. These 23 procedures (Table 1) accounted for more than 95% of the total number of patients reported in Phase I as receiving radiopharmaceuticals for diagnostic purposes. Unlike the Phase I study, therapy practices were not included in the Phase II questionnaire.

In 1969, questionnaires were mailed to 879 physicians, 85.2% of whom responded. Of these, 12.9% were no longer doing the particular procedure, and in 21.6% of the cases the radionuclide had been changed. A change of this magnitude in the 3 years between 1966

Table 1 Radionuclides Currently Used in Procedures Sampled

Procedure sampled	Total no. of physicians using procedure in 1969
^{32}P blood volume	14
^{51}Cr blood volume	37
^{57}Co vitamin B_{12}	39
^{60}Co vitamin B_{12}	34
^{125,131}I blood volume	35
^{125,131}I fat absorption	41
^{125,131}I kidney function	43
^{131}I thyroid function	38
^{99m}Tc brain scan	39
^{99m}Tc liver scan	36
^{85}Sr bone scan	44
^{87m}Sr bone scan	13
^{131}I thyroid scan	38
^{131}I lung scan	41
^{125,131}I placenta scan	41
^{131}I liver scan	41
^{131}I kidney scan	30
^{197}Hg kidney scan	39
^{198}Au liver scan	37
^{203}Hg kidney scan	31
^{203}Hg brain scan	36
^{197}Hg brain scan	39
^{51}Cr placenta scan	12
Total	798

*Summary of Report BRH/DMRE 70-1, prepared by Stanford Research Institute, Menlo Park, Calif., for Radioactive Materials Branch, Division of Medical Radiation Exposure, U. S. Department of Health, Education, and Welfare, Public Health Service, Bureau of Radiological Health, Rockville, Md. 20852.

†Report MORP-68-10, summarized in *Isotopes and Radiation Technology*, 6(4): 415-423 (Summer 1969).

Table 2 Place of Practice

Procedure	Percent of physicians doing procedure		
	Hospital practice	Individual office practice	Group practice outside hospital
^{51}Cr blood volume	94.7	–	5.3
^{57}Co vitamin B_{12}	87.7	9.1	3.2
^{60}Co vitamin B_{12}	89.4	–	10.6
^{125,131}I blood volume	92.0	5.1	2.9
^{125,131}I fat absorption	96.2	–	3.8
^{125,131}I kidney function	93.7	5.9	0.4
^{131}I thyroid function	81.2	15.4	3.4
^{99m}Tc brain scan	97.5	1.9	0.6
^{99m}Tc liver scan	100.0	–	–
^{85}Sr bone scan	92.9	3.5	3.6
^{131}I thyroid scan	76.4	16.3	7.3
^{131}I lung scan	100.0	–	–
^{125,131}I placenta scan	100.0	–	–
^{131}I liver scan	87.9	2.7	9.4
^{131}I kidney scan	96.5	–	3.5
^{197}Hg kidney scan	98.9	–	1.1
^{198}Au liver scan	86.4	7.5	6.1
^{203}Hg kidney scan	83.2	13.1	3.7
^{51}Cr placenta scan	100.0	–	–

and 1969 indicates the fast pace of technical development in the practice of nuclear medicine.

At least 75% of the physicians who perform any of the 23 specified procedures do so in hospitals (Table 2). The only procedures used by a significant fraction of the physicians (more than 10%) not engaged in hospital practice (i.e., private or group practice) include thyroid uptake and scanning, the two vitamin B_{12} malabsorption procedures, the two most widely used liver-scanning procedures, and the most widely used kidney-scanning procedure.

The only radionuclide widely procured by the physicians in the form of a generator is ^{99m}Tc. More than half the physicians procure unit doses of radiopharmaceuticals for the vitamin B_{12} malabsorption, the ^{125,131}I fat malabsorption, the ^{131}I-iodide thyroid uptake and scanning, and the ^{125,131}I human serum-albumin blood volume and placental-localization procedures. The majority of the physicians performing the remaining procedures under consideration procure the radiopharmaceutical in the form of multidose lots.

In all but three procedures, at least half the practitioners rely on the suppliers for quality control of the radiopharmaceutical. These three procedures use radionuclides that most of the practitioners procure as generator-produced material. Those practitioners who test the as-received material usually conduct an activity assay. In general, more of the physicians who procure a radionuclide in multidose lots conduct quality-control tests than do those who procure it in unit doses.

In all the scanning procedures except liver scanning with sulfur colloid tagged with ^{99m}Tc, more than 75% of the physicians reported no radiopharmaceutical modification. Tagging was also indicated as the modification made by about a third of the physicians performing placental localization with ^{51}Cr-labeled red-blood cells. Most of the other physicians conducting modifications perform only dilutions. The majority of the physicians who use modified radiopharmaceuticals conduct some testing before administration, and almost all conduct at least an activity assay.

Although the range of values of average administered activity was wide for most procedures, the average value (which is weighted to represent all physicians performing a procedure) compared favorably with the values reported in well-known references (Table 3).

More than two-thirds of the practitioners of three of the procedures using radioactive-iodine-tagged materials reported that they administered iodine-blocking agents to prevent accumulation of radioactive iodine in the thyroid (Table 4).

Table 3 Administered Radiopharmaceutical Dosages

Procedure	Administered activity per patient, μCi		
	Average of all practitioners	Range of values reported by sample of practitioners	
		Minimum	Maximum
^{51}Cr blood volume	27.33	3.00	50.00
^{57}Co vitamin B_{12}	0.50	0.10	1.40
^{125,131}I blood volume	5.50	0.50	22.50
^{125,131}I fat absorption	44.44	15.00	100.00
^{125,131}I kidney function	45.01	3.00	150.00
^{131}I thyroid function	36.86	2.50	100.00
^{99m}Tc brain scan	7,936.59	600.00	15,000.00
^{99m}Tc liver scan	2,971.61	700.00	8,000.00
^{85}Sr bone scan	104.97	50.00	300.00
^{131}I thyroid scan	56.86	10.00	150.00
^{131}I lung scan	260.44	100.00	350.00
^{125,131}I placenta scan	7.07	1.50	15.00
^{131}I liver scan	157.71	55.00	400.00
^{197}Hg kidney scan	144.42	45.00	300.00
^{198}Au liver scan	174.97	60.00	500.00
^{203}Hg kidney scan	116.58	70.00	280.00
^{51}Cr placenta scan	23.94	5.00	50.00

Table 4 Blocking-Agent Practices

Procedure	Percent of physicians doing procedure						
	Blocking		Blocking agents used				
	No	Yes	Iodides	Perchlorates	Mercurial diuretics	Vitamin B_{12}	Other
^{51}Cr blood volume	84.0	16.0	16.0	–	–	–	–
^{57}Co vitamin B_{12}	89.0	11.0	–	–	–	11.0	–
^{60}Co vitamin B_{12}	82.7	17.3	← Insufficient data →				
^{125,131}I blood volume	88.5	11.5	11.4	–	–	–	0.1
^{125,131}I fat absorption	32.2	67.8	67.8	–	–	–	–
^{125,131}I kidney function	95.9	4.1	4.1	–	–	–	–
^{131}I thyroid function	98.3	1.7	–	–	–	–	1.7
^{99m}Tc brain scan	35.1	64.9	18.9	37.4	2.7	–	5.9
^{99m}Tc liver scan	95.8	4.2	1.4	2.8	–	–	–
^{85}Sr bone scan	98.9	1.1	–	–	–	–	1.1
^{131}I thyroid scan	100	–	–	–	–	–	–
^{131}I lung scan	16.9	83.1	82.0	0.3	–	–	0.8
^{125,131}I placenta scan	9.8	90.2	90.2	–	–	–	–
^{131}I liver scan	72.6	27.4	27.4	–	–	–	–
^{131}I kidney scan	55.9	44.1	← Insufficient data →				
^{197}Hg kidney scan	87.6	12.4	–	–	12.4	–	–
^{198}Au liver scan	90.3	9.7	4.9	4.8	–	–	–
^{203}Hg kidney scan	86.9	13.1	–	–	13.1	–	–
^{51}Cr placenta scan	92.2	7.8	7.8	–	–	–	–

The practice of administering agents to accelerate the elimination of radionuclides from the patient is not widespread. It was reported (Table 5) as being used by more than 25% of the practitioners in only two procedures, and these are procedures that use accelerated elimination to improve diagnostic effectiveness.

Table 5 Accelerated-Elimination Practices

Procedure	Percent of physicians doing procedure	
	No	Yes
^{51}Cr blood volume	84	16
^{57}Co vitamin B_{12}	74	26
^{60}Co vitamin B_{12}	86	14
^{125,131}I blood volume	92	8
^{125,131}I fat absorption	99	1
^{125,131}I kidney function	95	5
^{131}I thyroid function	100	–
^{99m}Tc brain scan	98	2
^{99m}Tc liver scan	100	–
^{85}Sr bone scan	72	28
^{131}I thyroid scan	88	12
^{131}I lung scan	99	1
^{125,131}I placenta scan	97	3
^{131}I liver scan	100	–
^{131}I kidney scan	100	–
^{197}Hg kidney scan	96	4
^{198}Au liver scan	100	–
^{203}Hg kidney scan	92	8
^{51}Cr placenta scan	100	–

Almost all the practitioners calibrate their radiation detection and measuring instruments with some frequency—generally speaking, with each use or at least daily. The fraction of those who calibrate at increasing intervals decreases with the length of the interval.

The forms in which the radionuclides were reported as being used are

Procedure	Radionuclide	Form
Blood volume	^{32}P	Sodium phosphate
	^{51}Cr	Sodium chromate
	^{125,131}I	Albumin
Vitamin B_{12} malabsorption	^{57}Co	Cyanocobalamine
	^{60}Co	Cyanocobalamine
Fat malabsorption	^{125,131}I	Labeled fats and fatty acids
Kidney function	^{125,131}I	Sodium iodohippurate
Thyroid function	^{131}I	Sodium iodide
Thyroid scanning	^{131}I	Sodium iodide
Brain scanning	^{99m}Tc	Pertechnetate
	^{197}Hg	Labeled mercurials
	^{203}Hg	Labeled mercurials
Liver scanning	^{99m}Tc	Colloid
	^{131}I	Rose Bengal
	^{198}Au	Colloid
Bone scanning	^{85}Sr	Nitrate or chloride
	^{87m}Sr	Nitrate or chloride
Lung scanning	^{131}I	Albumin macroaggregates
Placenta scanning	^{125,131}I	Albumin
	^{51}Cr	Sodium chromate
Kidney scanning	^{131}I	Renal labeled compounds
	^{197}Hg	Labeled mercurials
	^{203}Hg	Labeled mercurials

The report itself gives, in tabular form, a detailed breakdown of the data arranged according to numerous schemes.

Section VI

Isotopes and Radiation Technology

Miscellaneous

Availability of Isotopes and Services

ISOTOPES SALES AGENTS

New England Nuclear Corp. has announced that it has been appointed a retail sales agent for Union Carbide's short-lived radioisotopes. The materials involved are ^{24}Na, ^{42}K, ^{82}Br, ^{64}Cu, ^{99}Mo, ^{131}Ba, ^{131}Cs, ^{198}Au, ^{114m}In, ^{197}Hg, and ^{169}Yb.

Mallinckrodt Chemical Works has closed its Sterling Forest and Flushing, N. Y., facilities and opened a new radiopharmaceutical production and distribution center at 463 Barel Street, Carlstadt, N. J. 07072. The center produces technetium products, including ^{99m}Tc generators, and supplies these and other short-lived isotopes to the medical community. A. J. Virginia has been appointed manager.

ADDITIONS TO THE ORNL STABLE-ISOTOPE INVENTORY

Recent additions to the Oak Ridge National Laboratory (ORNL) enriched-stable-isotope saleable inventory include the following:

Isotope	Purity, %	Amount available, g
^{33}S	86.8	0.09
^{58}Ni	99.8	30.5
^{61}Ni	92.9	2.4
^{61}Ni	90.4	3.3
^{62}Ni	96.1	4.7
^{112}Sn	79.6	3.8
^{136}Ce	21.7	1.4
^{154}Gd	66.5	6.7
^{166}Er	96.2	27.7
^{198}Hg	85.3	0.22
^{198}Hg	71.5	0.72
^{18}O	99.0	2.3
^{18}O	97.3	14.3

Planned additions to the inventory during the next 6 months are these:

Isotope	Lot No.	Estimated recovery, g	Estimated mass assay, at. %
^{121}Sb	NN 164502	50	99.5
^{123}Sb	NN 164601	35	98
^{125}Te	NS 166201	46	95
^{126}Te	NS 166301	112	98
^{142}Nd	OU 1794	235*	96
^{143}Nd	OU 1795	110*	80
^{144}Nd	OU 1796	210*	95
^{145}Nd	OU 1797	73*	75
^{146}Nd	OU 1798	150*	94
^{148}Nd	OU 1799	63*	88
^{150}Nd	OU 1800	55*	95
^{112}Sn	OT 1784	23.5†	>80
^{114}Sn	OT 1785	17‡	60
^{115}Sn	OT 1786	9.8‡	30
^{117}Sn	OT 1788	235‡	80
^{118}Sn	OT 1789	175‡	95
^{119}Sn	OT 1790	235‡	85
^{120}Sn	OT 1791	225‡	98
^{122}Sn	OT 1792	120‡	90
^{124}Sn	OT 1793	170‡	95

*Calculated to the end of August 1970.

†4.845 g of tin at 83.64% inventoried in July to provide material for sales.

‡Estimated to the end of October 1970.

NEW ISOTOPES AVAILABILITY FEATURE BEING INTRODUCED

Starting with this issue of *Isotopes and Radiation Technology*, there will be a regular reporting of the status and prognostications of the ORNL electromagnetic separations program. The information will cover the stable and radioisotope separations currently in progress and the planned additions to the inventory.

Isotope Separations

Stable. The stable isotopes of Fe, Hg, Nd, and Sn are currently being separated in 21 beta-type calutrons and three 255°-modified separators. These separators are being operated on a 5-day around-the-clock basis. The neodymium separation, which is proceeding in the three 255° units plus two 180° calutrons, will terminate in September 1970 and will very likely be replaced by a hafnium-isotope separation series. The tin-isotope separation will continue in eight calutron tanks until about Nov. 1, 1970, when it probably will be replaced by gallium. The iron and mercury separations are expected to continue through 1970.

The four separators in Building 9731 (two beta calutrons with 24-in. radius and two alpha machines with 48-in. radius) are being restored to service following the exchange of copper coils for the original silver coils. All four separators will be used for continuing development activities; however, cadmium-isotope separation will probably begin in the alpha tanks about Oct. 1, 1970, following completion of the coil installation. Development runs are now being made in the beta coil.

Radioactive. At the present time, two of the eight available separators in the alpha-contained area are being used to collect ~100 g of ^{233}U. This separation, also on a 5-day around-the-clock basis, is being made to reduce the ^{232}U content from ~800 ppB in the feed material to ~50 ppB so that the resulting ^{233}U can be used as a "cow" in producing ^{229}Th relatively free of ^{228}Th.

Future separations in the contained area include the recovery of ~2 g of ^{230}Th enriched to ~90%, ~500 g of ^{235}U enriched to >99%, and ~35 g of ^{241}Pu enriched to >95%.

NEW SERVICES IN RADIOISOTOPE FIELD

Accelerators Inc. has announced an agreement with Hughes Aircraft for Hughes to acquire a minority interest in Accelerators Inc. in exchange for which it will provide to Accelerators its ion-implantation-systems technology, its vacuum-equipment business, and cash. Accelerators Inc. has been a leading producer of ion-implantation systems for making semiconductors for the microelectronics industry. In addition, it has recently embarked on a program to broaden the applications of its particle accelerators to other fields, including neutron activation analysis, nondestructive evaluation of materials, and neutron radiography. E. Alfred Burrill, formerly Vice President of High Voltage Engineering Corporation, is Executive Vice President of Accelerators Inc.

Suntac Nuclear Corporation (1528 Walnut Street, Philadelphia, Pa. 19102) is a joint venture of the NUS Corporation and Catalytic, Inc., which provides services to various nuclear installations, including irradiation facilities and radioactive facilities of various types. Both parent companies have a long background of work in this field.

Medi-Physics, Inc. [5855 Christie Avenue, Emeryville, Calif. 94608; (415) 658-2184] has been formed to provide short-lived radiopharmaceuticals for use by physicians, primarily in the detection of cancerous growths. The facility is equipped with a compact cyclotron capable of providing large quantities of medically useful isotopes—actually the only cyclotron on the West Coast owned by a private corporation.

American Radiochemical Corp. [P. O. Box 1938, Sanford, Fla. 32771; (305) 322-8340] routinely manufactures and distributes ^{14}C-labeled compounds. The company also provides custom labeling of a number of enriched stable isotopes, including ^{2}H, ^{13}C, ^{15}N, ^{17}O, and ^{18}O.

Atomchem Corp. [1 E. Main Street, Suite 251, Bay Shore, N. Y. 11706; (516) 665-6550] has purchased the hot–cell equipment and associated inventory, originally belonging to Atlantic Research Corp., from Susquehanna Corp. in Alexandria, Va. Nuclear activities are carried out at the company's industrial reactor laboratory's hot cells in Plainsboro, N. J. [(609) 799-1809]. Emphasis will be placed in the area of encapsulated ^{90}Sr and ^{137}Cs sources for the controlled application of beta rays in the treatment of defects or lesions of the eye or in the nasopharynx, and gamma rays for interstitial and intracavity (body implants) treatment of tumors.

Industrial Nuclear Co., Inc. [9641 Lockland Road, Overland, Mo. 63114; (314) 426-2412] specializes in high-specific-activity ^{125}I- and ^{131}I-labeled proteins and hormones. The company also provides custom iodination service.

Automation Industries, Inc. [P. O. Box 245, Rt. 113, Phoenixville, Pa. 19460; (215) 933-8965] bought out the Instrument Division of Budd Co. in early 1969. In October 1969 they installed a new hot cell that is now being used for loading ^{192}Ir and ^{60}Co sources for industrial radiography. The cell can accommodate up to ~10 kCi of ^{60}Co.

Universal Radioisotopes Inc. [635 S. 31st Street, Richmond, Calif. 94804; (415) 237-2363] manufactures a variety of neutron sources (Ra–Be, Sb–Be,

Pu–Be, Th–Be), provides encapsulated sources containing millicurie quantities of ^{60}Co and ^{137}Cs, and furnishes reference calibration sources comprising alpha spectral sources (^{241}Am, ^{238}Pu, ^{239}Pu, ^{252}Cf) and sources involving essentially any other radioisotope requested by the customer.

Atlas Chemical Industries, Inc. [Wilmington, Del. 19899; (302) 658-9311, Ext. 8658] has recently announced two lines of ultrahigh-molecular-weight flocculents (trade name ATLASEP) for waste-water treatment. These polyelectrolytes are produced by gamma irradiation and are extremely efficient for removal of finely divided solids. (PSB)

NEW VERSION OF THE CHART OF THE NUCLIDES IS AVAILABLE

A new multicolor Chart of the Nuclides, which emphasizes nuclear power by-product elements and isotopes for large-scale applications, has been published by Battelle–Northwest. Based on an original chart worked out at General Electric's Knolls Atomic Power Laboratory, the modified version was developed by C. A. Rohrmann for the AEC's Division of Isotopes Development. It will be available from the Superintendent of Documents, Washington, D. C. 20402, for an estimated 50 cents, which includes mailing.

SHIELDING CONTAINERS FOR SMALL VOLUMES OF RADIOACTIVE SOLUTIONS

Shielding containers for radioisotope solutions, made of lead and having high-density lead-glass windows, are being marketed by Nuclear Associates, Westbury, N. Y. The Gamma Vue Shields completely protect a person handling the radioisotope, for example, a physician inserting a syringe into a vial inside the shield, while allowing full view of the contents.

BROCHURE ON RADIOPHARMACEUTICAL SPECIFICATIONS

Detailed specifications for 116 labeled compounds for radiopharmaceutical use are given in a brochure, *Spécification Radiopharmaceutique*, issued by Département des Radioéléments, C.E.N./Saclay, B.P. No. 2, 91, Gif-sur-Yvette, France. The brochure lists artificial radioisotope-labeled materials for medical usage, both diagnostic and therapeutic, as well as radioactive preparations used in in-vitro tests. Physical, chemical, and biological properties are included, together with methods used in quality control and testing. Thirty radioisotopes are involved. The brochure is supplied free upon request.

MOUND LABORATORY OFFERS ^{12}C, ^{13}C, AND ^{16}O AT REDUCED PRICES

Effective Sept. 1, 1970, Mound Laboratory is offering ^{12}C (99.95% enriched or better), ^{13}C (90% enriched or better), and ^{16}O (depleted in ^{17}O and ^{18}O) as follows:

Form	Price, $	Unit
^{12}C		
Carbon	1.75	Gram of carbon
^{13}C		
Carbon monoxide	31.00	Liter of gas
Carbon dioxide	31.00	Liter of gas
Methane	40.00	Liter of gas
Barium carbonate	4.50	Gram of compound
Carbon	73.00	Gram of carbon
^{16}O		
Oxygen	11.00	Liter of gas

Inquiries should be addressed to Monsanto Research Corporation, Mound Laboratory, Miamisburg, Ohio 45342.

AEC CHANGES PRICES OF ^{252}Cf, ^{16}O, ^{13}C

As a result of the economies resulting from large-scale production, the AEC has reduced by 100-fold its price for ^{252}Cf, effective when larger quantities become available in 1971. In contrast to the old price of $100 per 0.1 μg, the new price is $10 per μg, with abolishment of the former maximum order of 1 μg. The standard shipment is 1 mg, which will also incur a handling charge of $1600. Handling charges for shipments of between 10 μg and 1 mg are to be considered individually by the AEC but in no case will exceed the $1600.

AEC Activities

CONTRACTS AWARDED

New contracts recently awarded by the USAEC's Division of Isotopes Development were: to Washington State University, Pullman, for study of radioisotopic techniques to determine stream pollution resulting from paper-mill additives; to Panametrics for application of instruments, based on ^{85}Kr, to determine air pollution from automobile exhaust; to Zoller Dental Clinic of the University of Chicago for determining requirements for a radioisotopic radiation-backscatter gage for tooth-enamel-density measurements; and to McDonnell Douglas Astronautics Co., for the development of advanced radioisotope aerospace heaters, particularly as related to reentry fireball-survival capability.

Recent contract renewals were: to North Carolina State University, Raleigh, N. C., for basic and engineering studies of radiation-induced reactions in the liquid phase; to the Department of the Army, Coastal Engineering Research Center, Washington, D. C., for radioisotopic sand tracing in coastal waters; and to the General Electric Company, Philadelphia, Pa., for the design and fabrication of an integrated waste-management water system for aerospace applications utilizing radioisotopes for thermal energy.

NUCLIDE PRICE CHANGES

According to the *Federal Register,* **35**(103): 8300 (May 27, 1970), the USAEC has proposed to reduce the price for ^{241}Am from $1000 to $150 per gram, based on its full cost of production and distribution. Also proposed is a change from $1000 to $700 per gram in the base charge for 80% ^{238}Pu and the establishment of a base charge of $1250 per gram for ^{238}Pu enriched to $\geqslant$90% and containing not more than 0.3 part of ^{236}Pu per million.

FUNDS FOR RADIATION PROCESSING OF FOOD

The Joint Committee on Atomic Energy has recommended increases in the USAEC's FY 1971 requests for food-pasteurization-research funds. The recommendation, reflected in the House Appropriations Committee action, is that the $150,000 and $130,000 requested for the Division of Isotopes Development and the Division of Biology and Medicine programs, respectively, be increased to $270,000 each, subject to availability of funds. In addition, the House Committee on Armed Services has recommended $1,825,000 for the Army's food-sterilization program. The Army had not sought FY 1971 funds for the program, objecting to the estimated $2.7 million cost of obtaining food approvals from the Food and Drug Administration. The Committee feels that the recommended funding level for the Army Program would ensure U. S. leadership in the field and preserve the highly qualified scientific staff executing the program.

BROOKHAVEN MAKES CONSTRUCTION PRODUCTS FROM SEWAGE WASTE AND REFUSE

Sewage waste and refuse are substituted for normal aggregate in a concrete-type product under development at AEC's Brookhaven National Laboratory. The new polymer-loaded material has a compressive strength equal to or greater than ordinary cement concrete. Falling under the broad definition of concrete (any material that consists of a solid aggregate, not necessarily stone, bound together with a bonding agent), this new product has multiple advantages of recycling and reforming a waste material, thus reducing the waste-disposal problem and producing a material of possible use in foundation block.

The solid waste or refuse is mixed with cement to form a concrete, which is subsequently cured. For maximum strength, this concrete is impregnated with monomer that is then polymerized by radiation to give a high-strength sewage–cement–polymer concrete or refuse–cement–polymer concrete.

RADIOISOTOPE PRODUCTION TECHNOLOGY SEMINAR

Approximately 120 representatives of government and industry met in Oak Ridge, Tenn., on June 2–3, 1970, to discuss radioisotope-production technology developments. Formal papers, besides those on general subjects, covered AEC Laboratory developments on accelerator production of radionuclides, neutron products, fission-product recovery, biomedical isotopes, ^{252}Cf, beta sources, and shipping casks. Free single copies of resumés and list of attendees may be obtained by writing to the ORNL Isotopes Information Center.

Left to right are James W. Hitch, AEC Cochairman of the symposium; Charles A. Ziegler, Vice President of Panametrics, Inc., and Cochairman; Clarence E. Larson, Commissioner, Atomic Energy Commission; Frederick E. White, Professor of Physics, Boston College; and Philip S. Baker, Director, Isotopes Information Center, Oak Ridge National Laboratory, Oak Ridge, Tenn. Robert L. Carovillano, Cochairman for Boston College, was ill and unable to attend.

COMMISSIONER LARSON SPEAKS AT THIRD LOW-ENERGY CONFERENCE

Clarence E. Larson, Commissioner, Atomic Energy Commission, was the keynote speaker at a 3-day symposium conducted at Boston College recently. The Symposium on Low Energy X- and Gamma-Ray Sources and Applications was cosponsored by the AEC, Panametrics, Inc., of Waltham, Mass. (Research Division of Esterline Corporation, New York, N. Y.), and Boston College, June 10–12, 1970, at the Chestnut Hill Campus. (See the photograph above.)

This is the third such conference within the last 6 years to be cosponsored by the AEC, a university, and an industrial firm. The industrial firm that participates is chosen on the basis of its contribution to the field of X-ray and gamma-ray technology. Government interest in this particular symposium is evidenced by the fact that Commissioner Larson addressed the assembled scientists at the banquet held on Thursday evening.

DIVISION OF ISOTOPES DEVELOPMENT DESCRIBES PROGRESS ON RESEARCH AND DEVELOPMENT PROJECTS IN 1969

The progress made in research and development projects sponsored by the USAEC Division of Isotopes Development (DID) in 1969 has been described in a recent report published by the AEC. This 166-page report describes DID-sponsored work both at AEC laboratories and plants and at various industrial and academic facilities.

The seven program areas funded by the Division and the number of projects sponsored are as follows: Radioisotope Production and Materials, 44; Radiation Processing, 26; Radiation Analysis and Control, 16; Radiation Preservation of Food, 15; Environmental and Ocean Sciences, 11; Thermal Applications, 9; Technology Utilization, 1.

Among the projects summarized in the report are the production of isotopes and some of their applications as energy sources: ocean exploring, space travel, heart-assist devices, recovering potable water from human wastes, analysis of gunshot residue in crime investigations, detection of art forgeries, and refinement of concrete–polymer materials. A section on research in radiation preservation of foods list finfish, papayas, mangoes, strawberries, shrimp, and mushrooms as showing commercial prospects.

The report also reviews such environmental studies as measurement of sulfur dioxide in stack gases, analysis of pollutants in auto exhausts, stream-pollution problems of the pulp and paper industry, and a sand-tracing project to help solve problems of coastline maintenance and of fighting harbor and waterway pollution.

The report, TID-25372, is for sale at $3.00 by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Va. 22151. A limited number of copies are available through the Isotopes Information Center, Oak Ridge National Laboratory, P. O. Box X, Oak Ridge, Tenn. 37830.

General

PROGRESS IN RADIOISOTOPE-POWERED PACEMAKERS

The successful implantation of a radioisotope-powered pacemaker in a human patient in May has been reported from France. The UKAEA reports successful implantations in two dogs, one in February and the other in March. Both dogs are still doing well. The French and the British pacemakers are both fueled with ^{238}Pu, and the nuclear batteries have a design life of more than 10 years.

^{128}Xe PRODUCED FROM ^{127}I

An economical process for making ^{128}Xe from ^{127}I has been developed by Douglas United Nuclear. The ^{127}I is irradiated to form ^{128}I, which decays to ^{128}Xe. About 200 ml of ^{128}Xe has been produced for Argonne National Laboratory, who is using it in fuel-element testing.

FIVE MORE ^{90}Sr GENERATORS ORDERED

Teledyne's Isotopes has an order from the Navy for five 25-watt ^{90}Sr generators, to be used in remote land-based or marine weather stations. These bring to 21 the number of such sources in use.

RADIOISOTOPE-PACKAGING GUIDE

In a report by R. D. Seagren, "ORNL Isotopes Guide for the Packaging of Radioactive Materials for Transport" (ORNL-TM-2769, March 1970, available from CFSTI), packaging regulations are condensed for convenient use. The guide provides the necessary information for packaging, labeling, and marking routine shipments from ORNL, and supplements will be issued as regulations change.

IAEA SCHEDULES BIOPHYSICAL SYMPOSIUM

The IAEA has scheduled a symposium on Biophysical Aspects of Radiation Quality at Lucas Heights, N.S.W., Australia, March 8–12, 1971. The symposium can be considered a natural follow-up of two IAEA panels with the same title, held in Vienna in 1965 and 1967. Since then rapid development has taken place and a largely increasing number of scientists have become active in the field.

Papers have been invited on the following topics:

1. Microdosimetry: i.e., the evaluation of the microscopical patterns of the energy deposition in different media by various ionizing radiations, including theoretical analyses of local energy density spectra.
2. Biological action of ionizing radiation at the molecular level (e.g., breakage of DNA strands, interference with DNA, RNA and protein synthesis).
3. Biological implications of radiation chemistry (e.g., effects on biologically important molecules, effects on extracellular media).
4. Modifications of radiosensitivity of cells and tissues by changes in physical and chemical conditions (O_2 concentration, chemical protectors and sensitizers).
5. Biological implications of experiments designed to explore the relative biological effectiveness.
6. Interpretation of dose–effect relationships.
7. Time relationships and cellular kinetics (e.g., dose-rate and -fractionation effects, repair mechanisms).
8. Radiation quality and radiation protection.

The proceedings of the meeting will be published by the IAEA. Included will be all the papers presented orally, which will be printed in full in the language of submission, together with abstracts in the original language and in English, and a record of the discussions in English only.

The Scientific Secretary of the symposium is H. H. Eisenlohr, Division of Life Sciences, International Atomic Energy Agency, Kärntner Ring 11, P. O. Box 590, A-1011 Vienna, Austria.

The Administrative Secretary of the symposium is H. H. Storhaug, Division of Scientific and Technical Information, International Atomic Energy Agency, Kärntner Ring 11, P. O. Box 590, A-1011 Vienna, Austria.

IAEA SCHEDULES SYMPOSIUM ON USE OF RADIATION AND RADIOISOTOPES FOR GENETIC IMPROVEMENT OF INDUSTRIAL MICROORGANISMS

The International Atomic Energy Agency has chosen Mar. 29–Apr. 2, 1971, as the dates for a Vienna-based symposium, organized to review the

current results of research on microbial mutagenesis and recombination in relation to microbial fermentation. The participants will also explore promising new concepts and techniques relating to the genetic manipulation of microorganisms useful to fermentation processes through the application of atomic energy. Proposed topics include:

1. Current concepts regarding the mechanisms of radiation-induced genetic damage to biological macromolecules.

2. Current concepts regarding the mechanisms of radiation-induced mutagenesis and repair processes.

3. The mutagenic effectiveness of different doses and qualities of ionizing radiations in microbial systems.

4. The relative merits of ionizing radiations, ultraviolet, and chemicals in the induction of mutation for industrial purposes.

5. Recent developments in the selection of radiation-induced biochemical mutants of importance to the fermentation industries.

6. The use of radioisotope, radioactive tracer techniques and radiation-induced mutants in the biochemical analysis of biosynthetic pathways and their regulatory mechanisms.

7. The use of various recombination techniques to combine desirable properties of selected mutants for the improvement of fermentation efficiency.

8. Recent developments in the use of labeled metabolic precursor analogs and mutant strains in the synthesis of new products having important biological functions.

9. Applications of recent developments in radiation genetics and biochemistry of microorganisms in specific fermentation practices (antibiotics, essential amino acids, nucleotide derivatives, organic acids, etc.).

Participants, sponsored by the government of a member state of the IAEA or by an international organization invited to participate, must have applications submitted by the appropriate government not later than Dec. 28, 1970. Correspondence concerning the scientific matters, as well as the text of each paper, should be sent to The Scientific Secretary, Mr. R. Mukherjee, Division of Life Sciences, International Atomic Energy Agency, Kärntner Ring 11, P. O. Box 590, A-1011 Vienna, Austria. Correspondence on administrative matters should be sent directly to the Administrative Secretary, Miss C. H. de Mol van Otterloo, Division of Scientific and Technical Information, International Atomic Energy Agency, Kärntner Ring 11, P. O. Box 590, A-1011 Vienna, Austria.

THIRD INTERNATIONAL SYMPOSIUM ON PACKAGING AND TRANSPORTATION OF RADIOACTIVE MATERIALS

August 16–20, 1971, have been set as the dates for the Third International Symposium on the Packaging and Transportation of Radioactive Materials at Richland, Wash. The symposium is being sponsored by the U. S. Atomic Energy Commission; Atlantic Richfield Hanford Company; Battelle–Northwest; Douglas United Nuclear, Inc.; ITT/Federal Support Services, Inc.; J. A. Jones Construction Company; Vitro Corporation/Hanford Engineering Services; and WADCO Corporation. The program will cover the general topics: Administrative Experience; Package and Cask Development; Package and Cask Analysis; Transportation Experience; Progress in Quality Control and Standardization; and Future Trends and Needs for the Seventies. The symposium will also feature an exhibit of shipping containers for radioactive material, along with related technology. Symposium chairman is C. L. Brown, Battelle–Northwest, Richland, Wash. Telephone (509) 946-2418.

MEETING ON NEUTRON SOURCES

The American Nuclear Society (ANS) will hold a National Topical Meeting on neutron sources and applications in Augusta, Ga., Apr. 18–21, 1971. The meeting will be cosponsored by the local section and the Isotopes and Radiation Division of the ANS together with the Savannah River Operations Office of the U. S. Atomic Energy Commission. The program will deal with the production of neutron sources, their unique qualities, and their uses in industry, medical and forensic sciences, and exploratory and conservation areas. For further information, contact C. H. Ice, Savannah River Laboratory, Aiken, S. C. 29801.

NEUTRON PRODUCTS, INC., DELIVERS MILLIONTH CURIE

A milestone in radioisotope production and sales was reached May 12, 1970, when Neutron Products, Inc., delivered a quantity of ^{60}Co from its Dickerson, Md., facility to ARCO Chemical Company, a Division of Atlantic Richfield Company. Included in the delivery was the millionth curie of ^{60}Co produced in a power reactor for public sale.

Neutron Products, Inc., reached agreement in 1966 with Consumers Power Company, a large utility company serving Michigan, for production of ^{60}Co in available space in the core of the Big Rock Point power

reactor, Charlevoix, Mich. Under J. A. Ransohoff, Neutron Products had decided that there was sufficient market for ^{60}Co to justify production by a private company; until Neutron Products entered the field, all commercial production—worldwide—of radiation-processing-grade ^{60}Co was by sovereign governments. One other company was already producing tele-therapy-grade ^{60}Co.

At ceremonies marking the occasion of the millionth-curie sale, J. H. Campbell, president of Consumers Power Company, stressed the aggressiveness and practicality of the Neutron Products, Inc. venture. Consumers Power was not particularly interested in ^{60}Co production and had a number of elaborate programs with the USAEC and General Electric Company which resulted in some rather difficult production conditions. To help alleviate these conditions, Neutron Products built its own processing facilities to handle the ^{60}Co produced. Campbell cited the joint program as an example of how a small group of relatively uninfluential individuals with a good idea can be accommodated within large American industry. He added that Consumers Power is satisfied with both technology and economics and plans to continue producing ^{60}Co in its power reactors as a routine matter.

Also included in the ceremonies was a tour of the new materials irradiator of Neutron Products. This operating prototype, placed into operation early in 1969, is able to accommodate many different sizes and shapes of products to be irradiated. M. Turkanis, marketing director, pointed out that the system has provided trouble-free service under the high demand placed on it since early 1970. Neutron Products may soon offer facilities based on this design at a fixed price with guaranteed performance.

ARCO will use this millionth curie to process a wood–plastic composite marketed by ARCO as Perma-Grain. Other uses of ^{60}Co include sterilization of medical supplies, synthesis of certain chemicals, modification of polymers, treatment of cancer victims, and pasteurization and disinfestation of food. Ransohoff emphasized the size of the ^{60}Co market by pointing to the orders Neutron Products has on hand for delivery of 4.5 MCi of ^{60}Co during the next 3 years. (FEM)

^{252}Cf TO BE USED IN EXPLORATION OF OCEAN BOTTOM FOR MINERALS

Two investigations are currently under way with ^{252}Cf for evaluating the possibility of using activation analysis for underwater mineral exploration. Under a contract with the National Science Foundation, researchers of the University of Georgia are using a 197-μg ^{252}Cf neutron source in conjunction with the Westinghouse Deepstar 4000 submersible off the California coast. Laboratory tests have established limits of detection for minerals in the presence of seawater and under various thicknesses of sediment. In the undersea tests, scuba divers will place and mark specific samples, which the Deepstar system will then analyze by the neutron activation method. Data will appear on board as spectrums and will also be stored on magnetic tape for later detailed study. In addition to the ^{252}Cf neutron source, a compact neutron accelerator will be used in the tests.

In a separate contract, sponsored by AEC's Division of Isotopes Development, scientists at Pacific Northwest Laboratory have successfully demonstrated a nuclear probe to detect valuable minerals on the ocean floor. In the initial test, the combination of the probe, containing 200 μg of ^{252}Cf, and an extremely sensitive gamma-ray detector used successfully to detect mineral samples containing Au, Ag, Cu, and Mn. It is estimated that the device, which is designed to operate from either a surface ship or a submarine, can locate 20 to 30 elements in concentrations as low as 1 oz/ton.

BRITISH IMPERIAL CHEMICAL INDUSTRIES TO PRODUCE RADIOISOTOPES

ICI Ltd. plans to purchase a Triga reactor from Gulf General Atomic to produce short-half-life radioisotopes at their Teeside organic chemicals plant. These isotopes will be primarily those which, because of the distance of Teeside from British producers, cannot be supplied by the commercial vendors.

NUCLEAR ELECTRONICS

By Emil Kowalski, Lecturer, Institute of Applied Physics, University of Berne, Switzerland. Published by Springer-Verlag, New York, 1970 (402 pp., 337 figs., 918 refs.; hardback, $26.40).

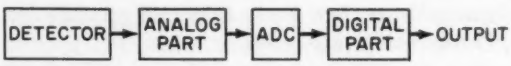
Supplementary Keywords: *book review; textbook; review, technical; bibliography; theory, applied; instrument; design; measurement and control system; industry; industry, electronics; biology; physics; radiochemistry; counting; luminescence; Mössbauer effect; ionization of gas; data handling; semiconductor; crystal.*

A close relation exists between electronics and radiation measurements in nuclear physics. This rela-

tion is evident from the large number of electronic measuring instruments used in pure or applied nuclear research, radiation protection, and the application of radioisotopes. Nuclear electronics has enjoyed such rapid growth that heretofore no summary of the subject has been available. To provide such a summary, Professor Kowalski supplemented the script of his lectures with a literature review and thus contributed *Nuclear Electronics,* which he says could be called a monograph with the character of a textbook. It is the only complete, up-to-date monograph that deals with the specialized electronic circuits and instruments used in nuclear radiation metrology. It covers the literature through 1968. Its systematic structure reflects the author's effort to ensure the continuance of its value as a reference work for years to come. The book is intended primarily for the experimental physicist but is also useful in the training of electronics engineers and as a reference for technicians. For conciseness, the general concepts of electronics are taken for granted, and certain basic knowledge is assumed.

The object of *Nuclear Electronics* is to emphasize the part of signal processing that is characteristic of nuclear physics. Only pulse techniques deal adequately with the quantum character of nuclear processes. In awareness of their importance, the author has devoted his descriptions only to circuits for pulse signals. A detector of the nuclear process gives rise to a current or voltage pulse. The pulse is correlated with the time instant of the nuclear process and carries most of its information in a continuous manner. The representation of data by a continuously variable parameter is an analog representation. Because it is very difficult to process analog signals, they are converted as quickly as possible to *digital* signals, which are then processed simply.

Electronic apparatus for nuclear research usually consists of a detector, analog part, analog-to-digital converter (ADC), and digital part for signal processing. Professor Kowalski represents the array as



The arrangement of his book follows this array. He describes various radiation detectors, preamplifiers, and auxiliary circuits (Chap. 2). The analog operation of the detector signals is discussed, especially the complex problem of pulse forming and amplification (Chap. 3). The various types of ADC's for conversion of pulse amplitude, pulse shape, or time interval between two pulses are described (Chaps. 4 and 5). A discussion is also included of the digital circuits found in data-processing assemblies and computers, industrial measurement and control systems, and nuclear measuring equipment (Chap. 6). Scaler assemblies and analyzers for nuclear research are reviewed (Chap. 7). A discussion of Laplace transform calculus and of noise is appended (Chap. 8).

The book should be extremely useful to those working in the field of radiation biophysics, nuclear physics, electronics, photochemistry, or radiochemistry. (HPR)

POLYMER–CEMENT CONCRETES AND POLYMER–CONCRETES

By V. I. Solomatov, translated from the Russian and edited by M. Gerrard, R. E. Greene, and P. S. Baker, Isotopes Information Center, AEC-tr-7147, originally published by Izdatel'stvo Literatury po Stroitel'stva, Moscow, 1967.

Supplementary Keywords: *review, technical; polymerization; industry; industry, building; industry, plastics; industry, stone, clay, and glass; USSR.*

This book is the first attempt at generalization and systematization of theoretical and practical knowledge of the technology and use of polymer–cement concretes and polymer–concretes—the new high-strength, stable materials whose properties can be changed at will within wide limits. Their high static and dynamic strengths and their resistance to wear and chemicals permit their wide use for chemical-resistant equipment, storage vessels and pipelines for corrosive or biologically active liquids, chemical-resistant floors, sewage systems, and many other purposes. The book was written for construction engineers and for industrial workers who use construction materials.

Translation of the Russian book was undertaken in the Isotopes Information Center at the request of the USAEC's Division of Isotopes Development (DID), which is sponsoring research in this field. For obvious reasons the DID work is primarily directed toward the use of radiation to bring about polymerization—a technique which, unfortunately, is not considered in this book. Nevertheless, the wealth of background information on properties and uses of polymer-based concretes was thought to be valuable to persons working in this field. (MG)

GOLDBLITH REAPS REWARDS

Dr. Samuel A. Goldblith, a foremost proponent of food irradiation, continues to receive awards for his outstanding contributions to food technology. The 1970 Nicholas Appert Award has been awarded Dr. Goldblith by the Institute of Food Technologists (IFT). Named for the inventor of canning, the award was originated by the Chicago Section of the IFT and consists of a bronze medal and an honorarium. Last year Dr. Goldblith was awarded the Babcock–Hart Award by the IFT.

Dr. Goldblith has been extremely active in the field of food technology since his graduation from Massachusetts Institute of Technology (MIT) in 1940; he has published more than 175 papers on the preservation and production of better, more nutritious foods. He holds the position of Deputy Department Head of the Department of Nutrition and Food Science at MIT. His major contributions in teaching and research have been in radiation preservation of foods, freeze hydration of foods, food processing, and in microwaves and their applications to food processing. Dr. Goldblith has received a number of other awards during his career, including the Distinguished Food Scientist Award from the New York Section of the IFT in 1969. He is an outstanding research scientist and a stimulating instructor.

CUMULATIVE INDEX FOR *ISOTOPES AND RADIATION TECHNOLOGY* AVAILABLE

The Isotopes Information Center has developed a permuted index for the first seven volumes of *Isotopes and Radiation Technology*. Copies may be obtained by writing to Isotopes Information Center, Oak Ridge National Laboratory, Post Office Box X, Oak Ridge, Tenn. 37830.

IAEA PUBLISHES SAFETY DESIGN MANUAL FOR RADIOISOTOPE POWER GENERATORS

IAEA, Vienna, Austria, *Guide to the Safe Design, Construction, and Use of Radioisotope Power Generators for Certain Land and Sea Applications*, Safety Series No. 33, STI/PUB/246, Vienna, 1970. 33 pages, $1.50. Available from Unipub, Inc., P. O. Box 433, New York, N. Y. 10016. (Also published in French, Russian, and Spanish)

As a result of the increasing development and production of certain types of radioisotopic power generators, a need has arisen for internationally acceptable recommendations governing the health and safety aspects of their construction and use. This guide is intended to facilitate the establishment of an adequate standard of safety in the design, construction and installation, and use of radioisotope power generators, and in their ultimate disposal.

The first part of the guide delineates scope (generators for use on land and under the sea), defines and explains terms, outlines design principles, siting precautions, etc., for the two types of generators, and indicates methods of disposal.

The second part comprises three appendixes: Capsule Tests, Fuel Capsule Housing Tests, and Suggested Format of Safety Assessment for Submission to the Competent Authority.

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December 1969

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